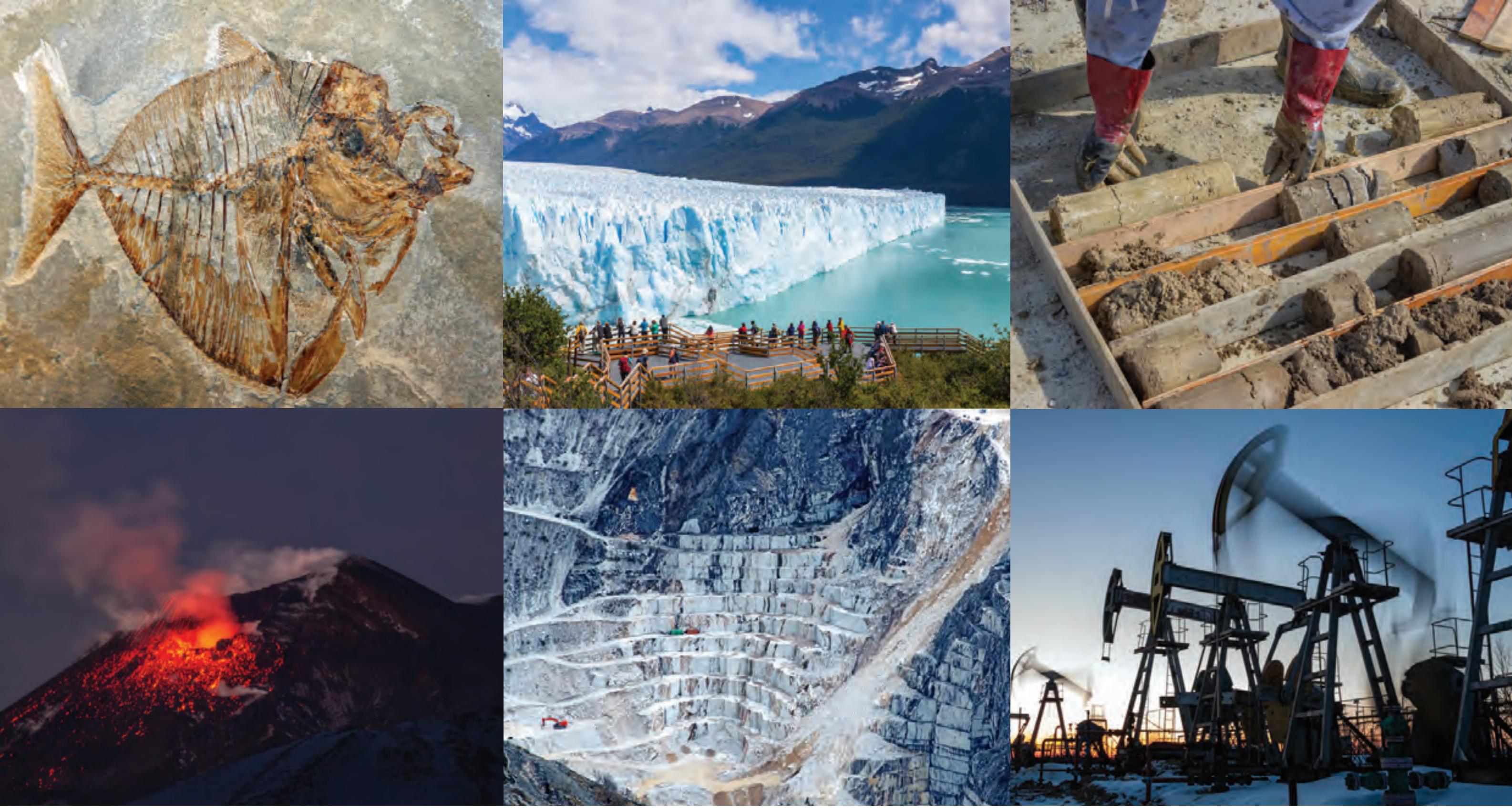

# GEOBONN 2018

2–6 September 2018 I Bonn I Germany

Living Earth

# Abstracts

DGGV Deutsche Geologische Gesellschaft Geologische Vereinigung

DMG Deutsche Mineralogische Gesellschaft

Dachverband Geowissenschaften DVGeo

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# Public Lecture / Plenaries

**Public Evening Lecture / Öffentlicher Abendvortrag**

## Herausforderung Klimawandel

**Mojib Latif**

*GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Germany*

Das Klimaproblem steht seit vielen Jahren im Blickpunkt des öffentlichen Interesses. Der Geochemiker Roger Revelle hatte bereits vor über einem halben Jahrhundert die ungeheure Dimension der menschlichen Klimabeeinflussung beschrieben, in dem er von einem „gigantischen Experiment“ sprach, das die Menschen anstellten. Das Klimaproblem ist hauptsächlich ein Energieproblem und hängt eng mit der Verfeuerung der fossilen Brennstoffe - Kohle, Erdöl und Erdgas – zur Energiegewinnung zusammen. Dabei entstehen große Mengen des Gases Kohlendioxid ($CO_2$). Das Gas reichert sich allmählich in der Luft an, was zwangsläufig durch den sich verstärkenden Treibhauseffekt zur Erderwärmung führt. Was kann man heute schon an Veränderungen messen? Wie wird sich das Klima in der Zukunft ändern? Wie ist die internationale Klimapolitik zu bewerten?

**Plenary Talk**

## Gravity drives Great Earthquakes

**Gordon Lister**

*Australian National University, Australia*

This presentation discusses the role of gravity in driving Great Earthquakes, with data from the 2004 Great Sumatran Earthquake, and from the 2011 Tohoku-oki Great Earthquake. We show the Sumatran segments of the 2004 megathrust event were subject to compression in a direction near to orthogonal with the margin trend, consistent with effect of relative movement of the adjacent tectonic plates. In contrast, the crust above the Andaman Sea segments was subject to margin-orthogonal extension, consistent with motion towards the gravitational potential well accumulated due to prior lateral (westward) rollback of the subducting edge of the northward moving Indian plate. The story is quite different for the 2011 Tohoku-oki earthquake, however. Here, lineament-bounded extensional channels mark segments of the East Japan megathrust with different geodynamic behaviour to that of adjacent compressional segments. This pattern implies movement in the extensional channel driven by seaward gravitational collapse of the Japanese crust, requiring the rupture to have offered negligible resistance. The upward migration of fluids and magma would explain the prominent volcanic lineaments. Fluid activity would also have reduced effective stress on the overlying megathrust, or produced lubricating mineralogy as the megathrust slowly unlocked in the decade preceding catastrophic failure.

The consistent landward-dip of normal faults at the trenchward-end of the extensional channel suggests an array of tilt-blocks linking to a detachment beneath a slowly slumping slab sheet, with a strike dimension comparable to the width of the extensional channel. Again, nevertheless, although for different geodynamic reasons, gravity has driven a Great Earthquake.

**Plenary Talk**

## The integument of fossil vertebrates: evolution, physiology and behaviour

**Maria McNamara**

*University College Cork, Ireland;* maria.mcnamara@ucc.ie

The integument of vertebrates has diverse functions in mechanical protection, homeostasis, locomotion, respiration and coloration. Many vertebrate fossils preserve evidence of the integument as mineralized or carbonaceous remains. Where the integument is preserved as mineralized remains, only selected tissue components survive fossilization, for reasons that are poorly understood. Carbonaceous remains of the integument usually comprise primarily melanosomes, which are cellular organelles rich in the decay-resistant pigment melanin. Much previous work on vertebrate fossil melanin has focused on reconstructions of integumentary color and its associated ecological functions. Major questions remain, however, regarding the broader biological distribution, chemistry and taphonomy of melanin and melanosomes. Here I will review recent and current work by my group that sheds light on each of these major issues, with broader implications for our interpretation of the soft tissue anatomy, physiology and behaviour of fossil vertebrates.

**Plenary Talk**

## Exploring the Symmetry of Seafloor Spreading

**William B F Ryan**

*Lamont-Doherty Earth Observatory of Columbia University, United States of America*

The discovery in 1966 by Pitman and Heirtzler of the remarkable symmetry of magnetic anomalies across the axis of Pacific-Antarctic mid-ocean ridge broke the barrier of resistance to the earlier hypotheses of continental drift and seafloor spreading. Although Vine and Mathews had already proposed that lava erupted from fissures at the crest of the ridge acquired a magnetization in the direction of the geomagnetic field at the time of cooling, the pattern of reversals in their model was ad hoc and not observed in nature. However, as soon as the same pattern of magnetic stripes in the southwest Pacific was repeated in the northeast Pacific and again in the North and South Atlantic, all doubt vanished. Presently we have a near-global coverage of magnetic anomalies. From this compilation come remarkable maps of seafloor ages. However, magnetic reversal boundaries imprinted in oceanic crust occur at spacings of tens to hundreds of kilometers depending upon spreading rates. On the other hand, abyssal hill spacing, as revealed in multibeam swath mapping and deep-towed side-looking sonar imagery, is considerably tighter and is typically just a few kilometers or less. Investigations of the Juan de Fuca, East Pacific, and Pacific-Antarctic spreading centers show that abyssal hills are symmetric across accreting plate boundaries and represent the flanks of split axial volcanic ridges. The episodes of volcanic outpouring to create the axial ridge and its subsequent splitting to create the median depression have periods similar to Milankovitch cycles (precession, obliquity and eccentricity). A link occurs between these cycles and sea level fall. The loss of the weight of seawater induces mantle decompression and subsequent increase in melt production and delivery to the spreading axis. In this presentation we will look at the creation of abyssal hills and their corresponding magnetic stripes at steps of 25 ky for a duration of 10 my to witness a symmetric pattern of ocean crust production caused by the waxing and waning of magma supply.

**Plenary Talk**

## “Deep Earth controls over the surface environment on the early Earth”?

**Balz S. Kamber**

*Queensland University of Technology, Brisbane, Australia*

The Earth’s Precambrian sedimentary record reveals a complex evolution of the planet’s surface environment, highlighting the importance of bio-geo-chemical interaction, particularly the long-term effect of biology on key elemental cycles, including C, O, N, S, Fe, Mo, and U. In these discussions, deep Earth control is often regarded to be of only secondary importance, a view that may need revisiting.

It is widely acknowledged that the early Earth was producing substantially more radioactive heat than at present (2 x at 2.7 Ga) and likely still contained more primordial heat. Most researchers equate this with an ‘overall’ substantially hotter Archaean mantle. Alternatively, the Archaean Earth was more efficient at losing heat and maintained a relatively cool upper mantle throughout. New statistical analysis of the vast published geochemical database for Archaean mafic and ultramafic rocks shows a clear bimodal distribution. The composition of the basaltic mode remained relatively unchanged through time but in the Archaean, there was an additional komatiitic high-Mg mode. This observation strongly argues against secular change in the potential temperature of the convecting upper mantle, instead suggesting a relatively cool asthenosphere but much hotter Archaean plumes or upwellings from the deeper mantle.

These hot upwellings had very important consequences for the surface environment. The common presence of ultramafic volcanic rocks on the seafloor exposed olivine to hydrothermal alteration. The resulting serpentinisation reactions led to formation of metal alloys that acted as catalysts for Fischer–Tropsch reactions, supplying the early ocean with molecular building blocks for life-forming reactions. Where large mantle upwellings occurred in the oceanic realm, oceanic plateaus appeared, which are a rare sight on the present planet but could have been common on the early Earth. The rare earth element pattern and Sr-isotope composition of the Archaean seawater suggest that mafic/ultramafic plateaus might have breached the surface and been a dominant land type. Weathering on these plateaus released significant loads of many compatible elements into the ocean. The high oceanic inventory of some of these elements may have influenced biochemical pathways and evolution (e.g. Ni promoting methanogens). A currently underexplored aspects of the Archaean surface is the weathering pathway of common mafic to ultramafic volcanic ashes and its effect one residual land mineralogy and sediment.

The rapid disappearance of common ultramafic volcanic rocks at ca. 2.5 Ga predates the Great Oxygenation Event by just over 100 Ma: is this a fortuitous coincidence or a causal relationship?

# Topic 1: Early Earth

## 1a) Cosmochemistry – from dust to planets

Talk

### In search of nucleosynthetic Sn anomalies in chondrites

**Alessandro Bragagni, Frank Wombacher, Maria Kirchenbaur, Ninja Braukmüller, Bo-Magnus Elfers, Carsten Münker**

*Institut für Geologie und Mineralogie, Universität zu Köln, Germany*

Nucleosynthetic isotope anomalies in meteorites reveal the variable distribution of different presolar materials in early solar system matter, ultimately reflecting an incomplete isotopic homogenization. So far, nucleosynthetic anomalies were observed for many refractory elements [e.g. 1 for a review], but only few studies focused on moderately-volatile elements (MVE, half condensation temperatures between 1060 and 664 K) [2, 3, 4]. Nucleosynthetic isotope anomalies in MVE can provide constrains on the thermic conditions and physical processes occurring in the early stages of the solar system. In fact, nucleosynthetic isotope anomalies in MVE are not expected to survive heating events that could have occurred in the solar nebula or within parent bodies. Among the MVE, Sn is one of the most promising elements for nucleosynthetic studies, having at least two nuclides prevalently produced during the p- (i.e. $^{112}Sn$ and $^{114}Sn$), s- ($^{116}Sn$ and $^{120}Sn$), and r-processes ($^{122}Sn$ and $^{124}Sn$), respectively.

For the separation of Sn, a new chemical procedure was developed, based on anion and TBP resins. The TBP resin yields cleaner Sn fractions compared to TRU resin [e.g. 3]. For instance, TBP resin removes actinides more efficiently, minimizing the possible $^{238}U^{++}$ interference on $^{119}Sn$. Tin isotope analyses were performed on a Thermo-Fisher Neptune plus equipped with $10^{13}\Omega$ amplifiers. In order to measure the ten Sn isotopes and monitor $^{111}Cd$, $^{113}In$, $^{125\text{-}126}Te$ for isobaric interferences, two different cup configurations were employed for light and heavy Sn isotopes. Mass bias correction was performed using $^{118}Sn/^{120}Sn$ or $^{116}Sn/^{120}Sn$. Over the course of one analytical session, multiple measurements of the NIST 3161a standard solution yield 2RSD <±100 ppm for $^{112\text{-}114\text{-}115}Sn/^{120}Sn$, and <±20 ppm for $^{116\text{-}117\text{-}118\text{-}119\text{-}122\text{-}124}Sn/^{120}Sn$.

First results on bulk meteorites show no resolvable anomaly, except for low $^{124}Sn/^{120}Sn$ in the Murchison CM2 meteorite, which is in agreement with previous findings [3] and also consistent with an s-process excess. In addition, Roosevelt H3.4 meteorite shows anomalously low $^{117}Sn/^{120}Sn$ and $^{119}Sn/^{120}Sn$, possibly suggesting mass independent fractionation due to nuclear field shift effects [5, 6].

[1] Qin and Carlson (2016) Geochem. J., 50, 43-65. [2] Savage *et al.* (2014) MAPS, 49, A356. [3] Friebel *et al.* (2017) Goldschmidt conference abstr. [4] Fukami and Yokoyama (2017) Geochem. J., 51, 17-29. [5] Moynier *et al.* (2009) CGA, 632, 234–239. [6] Malinovskiy *et al.* (2009) Environ.Sci.Technol., 43, 4399-4404

Talk

### A hockeystick volatile element depletion pattern for the Earth

**Ninja Braukmüller, Frank Wombacher, Carsten Münker**

*Universität zu Köln, Germany*

All known inner solar system bodies are depleted in volatile elements relative to CI chondrites, which provide a reference composition of the solar system. The composition of the Earth predominantly depends on the composition of its building blocks. While the isotope composition of the Earth suggests a link to enstatite chondrites [1], refractory and main component lithophile element abundances indicate compositional similarities to carbonaceous chondrites (CCs) [2].

The characteristic volatile element depletion trend of the bulk Earth (BE) is described by lithophile volatile elements in the bulk silicate Earth (BSE), since these presumably did not partition into the core and thus represent the pristine BE composition. Although volatile elements are more depleted in the Earth compared to any known CC group, it is generally believed that volatile elements in the Earth expand the CC trend, with gradually decreasing abundances towards volatile elements with increasingly lower 50% $T_C$ [2]. Our analyses of volatile element abundances in CCs, however, reveal that this monotonous depletion trend is only valid for elements with 50% $T_C$ between 1200 and 800 K. Volatile elements with 50% $T_C$ between 800 and 500 K are unfractionated from each other and form characteristic abundance plateaus relative to CI for all analyzed CC groups [3]. We therefore refer to the former group as slope volatile elements and and the latter as plateau volatile elements. As a function of 50% $T_C$, slope and plateau volatile elements together form a characteristic hockeystick pattern.

Due to the close compositional relationship between the Earth and CCs, it is highly likely that the BE also exhibits a hockeystick volatile element depletion pattern. This suggestion is supported by the chondritic ratios observed for the lithophile halogenes Cl, I and Br [4] and the chondritic Zn/In ratio in the BSE where the more volatile element In is not preferentially lost relative to Zn. A hockeystick volatile element depletion trend would explain the apparent overabundance of In [5] without the need of terrestrial building blocks with unusual In enrichments [6] or for melting and volatile loss from precursor bodies or during the giant Moon-forming impact [7].

[1] Dauphas (2017) *Nature* **541**, 521-524. [2] Palme et al. (2014) *Treatise of Geochemistry.* [3] Braukmüller et al. (in revision). [4] Clay et al. (2017) *Nature* **551**, 614-61. [5] Witt-Eickschen et al. (2009) *GCA* **73,** 1755-1778. [6] Wang et al. (2016) *EPSL* **435**, 136-146. [7] Norris and Wood (2017) *Nature* **549**, 507-510.

**Talk**

## Isotope anomalies – a Rosetta stone for deciphering planetary genetics and the solar system's dynamic evolution

**Christoph Burkhardt**

*WWU Münster, Germany*

We are living in exciting times for research in star and planet formation. Improvements of observational capabilities in the last decade revealed that planetary systems around stars are rather the rule than the exception, and the observation of young stellar objects now allows to study protoplanetary disks and planet formation *in-situ*. As these findings offer a fresh perspective on our own solar system, understanding its formation through the analysis of meteorites also took big leaps forward in the last years. This progress is in particular driven by the discovery of minute nucleosynthetic isotope anomalies in meteorites and their components. These mass-independent isotope variations are the result of variable processing of presolar mineral phases in different regions of the protoplanetary disk, and can thus be used as a tool for tracing genetic relations among planetary materials, an application which is currently revolutionizing our understanding of the dynamic evolution of the solar system.

In this talk I will provide an overview of the state of the art in this emerging field, with a focus on how nucleosynthetic anomalies in bulk planetary bodies are affecting our understanding of Earth's formation and evolution. In particular I will focus on how nucleosynthetic anomalies are used to constrain Earth's accretion history, how they affect radiometric dating systems and thereby compositional and dynamic models of the Earth, and what they might tell us about the formation of Jupiter and the delivery of water/volatiles to the inner solar system.

**Poster**

## Oxygen isotope fractionation in equilibrated high-temperature feldspar-rich rocks

**Meike B. Fischer[1,2], Benjamin Maksumic[2], Stefan T. M. Peters[2], Sukanya Sengupta[2], Paul Hartogh[1], Andreas Pack[2]**

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This study is inspired by the debate on the usability of oxygen isotope compositions obtained from feldspar-rich lunar rocks. It has been proposed that anorthite-rich plagioclase shows a preference for $^{16}O$ over $^{17}O$ and $^{18}O$ leading to a systematically lower $\Delta'^{17}O$ in lunar anorthosites compared to basalts [1]. Crystal chemical effects of the tectosilicate lattice structure were discussed as possible explanation for the lower $\Delta'^{17}O$ values of plagioclase. Based on this observation, interpreting the oxygen isotope data of felsic lunar rocks according to normal mass fractionation laws might be insufficient.

We present new high-precision oxygen isotope data on co-genetic, equilibrated mineral assemblages of terrestrial igneous and high-temperature metamorphic rocks. Samples were checked for equilibration by means of petrography and mineral chemistry. Oxygen isotope measurements were conducted by laser fluorination. An improved measurement protocol was developed for feldspar.

We aim to verify whether the observed low $\Delta'^{17}O$ of the mineral plagioclase is real. We apply the results on the question of apparently lower $\Delta'^{17}O$ of lunar anorthosites when compared to lunar mare basalts.

[1] Kohl I. E. et al. (2017) Lunar Planet. Sci. Conf. 48, abstract #2292.

**Talk**

## The search for volatile-rich building blocks in the Archean mantle

**Mario Fischer-Gödde[1], Bo-Magnus Elfers[1], Carsten Münker[1], Wolfgang Maier[2], Kristoffer Szilas[3], Hugh Smithies[4], Tomoaki Morishita[5]**

*[1]University of Cologne, Germany; [2]Cardiff University, UK; [3]University of Copenhagen, Denmark; [4]DMIRS, WA Gov., Australia; [5]Kanazawa University, Japan*

The Earth formed by accretion of numerous planetesimals and planetary embryos originating from various heliocentric distances. Depending on the location of their formation region these planetary building blocks are characterized by different contents of water and volatiles with the highest volatile abundances expected in objects formed at greater heliocentric distance [1]. While it is largely accepted that water and other volatiles were brought to the Earth by the accretion of carbonaceous chondrite-like materials [2,3], the timing for the accretion of these volatile-rich objects has been the subject of significant debate [4-6].

It has been proposed that water and volatiles were added to the Earth during late accretion of a late veneer after core formation had ceased [4-7]. However, the accretion of volatile-rich materials as part of the late veneer cannot be reconciled with recently reported Ru isotopic data for primitive meteorites [8,9]. This is because the Ru in the Earth's mantle almost exclusively derives from the late veneer and volatile-rich meteorites formed at greater heliocentric distance are characterized by large Ru isotope anomalies [9]. Thus, the late veneer cannot be comprised of volatile-rich carbonaceous chondrite-like asteroids. The Earth must therefore have accreted its budget of volatile elements during earlier stages of accretion.

Here we investigate the presence of volatile-rich material in the pre-late veneer mantle using Ru isotopes. The pre-late veneer mantle has been suggested to be preserved in some Archaean igneous rocks, based on lower PGE abundances inferred for the mantle source of these rocks. Using chromitites and komatiites from different Archean mantle domains from South Africa, Pilbara and Greenland, we will test whether nucleosynthetic Ru isotope anomalies imparted by the accretion of carbonaceous chondrite material can be observed in the pre-late veneer mantle. The presence of such anomalies would provide key constraints on the timing of volatile accretion on Earth.

[1] Morbidelli, A. et al. (2000) MAPS 35, 1309-1320. [2] Marty, B. (2012) EPSL 313-314, 56-66. [3] Alexander, C.M.O.'D (2012) Science 337, 721-723. [4] Albarède, F. (2009) Nature 461, 1227-1233. [5] Albarède, F. et al. (2013) Icarus 222, 44-52. [6] Ballhaus, C. et al. (2013) EPSL 363, 237-245. [7] Wang, Z. & Becker, H. (2013) Nature 499, 328-331. [8] Fischer-Gödde, M. et al. (2015) GCA 168, 151-171. [9] Fischer-Gödde, M. & Kleine, T. (2017) Nature 541, 525-527.

**Talk**

## Extreme nebular nitrogen processing documented by iron nitride in Acfer 094?

**Dennis Harries, Moritz Barth, Falko Langenhorst**

*Friedrich-Schiller-Universität Jena, Germany*

In the search of inorganically bound nitrogen we have studied a thin section of Acfer 094 (PL93022) by scanning electron microscopy and X-ray spectroscopy imaging, specifically targeting metal grains. Elemental distribution maps revealed µm-sized nitrogen anomalies in at least two of more than 30 metal grains studied. Electron diffraction identified one inclusion as cubic $(Fe,Ni)_4N$ (roaldite). The roaldite appears to be a platelet-shaped precipitate. To our knowledge this is the first report of roaldite from a chondritic meteorite. The formation of CrN and $Fe_4N$ in Cr- and Ni-bearing Fe-rich alloys requires intense nitrogen activities (Fegley 1983; Harries et al. 2015). A rough estimate of the volume ratio of the roaldite lamella and the total grain volume indicates a bulk nitrogen content on the order of 10 ppm N. This is low compared to N concentrations on the order of 100 to 1000s ppm estimated for CrN-bearing grains (Harries et al. 2015; Barth et al. 2016), but in general similar to N concentrations in iron meteorites (Fegley 1983).

Equilibrium thermodynamics indicate that both the N content of iron meteorites and chondritic metal as well as the stable coexistence of roaldite and Fe,Ni alloy in a gas of solar composition would require $N_2$ pressures orders of magnitude larger than reasonably anticipated for the solar protoplanetary disk. At $10^{-3}$ bar at most 0.08 ppm N would dissolve in Fe,Ni alloy, and the equilibrium between kamacite and roaldite would require $N_2$ partial pressures on the order of 400-4000 bar at 300-800 K (Fegley 1983). Therefore, the high nitrogen activities required to stabilize nitrides in a nebular setting demand non-equilibrium chemistry (Fegley 1983), which we hypothesize to involve metastable $NH_3$ released from evaporated ices at nebular pressures (Harries et al. 2015). The formation of $Fe_4N$ requires much larger nitrogen activities than CrN, indicating that the enrichment of $NH_3$ relative to $H_2$ and $H_2O$ must have been extreme.

References: Harries D. et al. (2015) *Nature Geoscience* 8:97–101. Barth M. I. F. et al. (2016) *79th Annual Meeting of the Meteoritical Society*, Abstract #6334. Barth M. I. F. et al. (2016) *Meteoritics & Planetary Science* 53:187–203. Fegley B. (1983) *Lunar and Planetary Science Conference Proceedings* 13:853–868. The DFG supported us within SPP 1385 (grant HA7187/1-1) and funded the FIB-TEM facilities (grant LA830/14-1). We are grateful to A. Bischoff for providing us the thin section of Acfer 094.

**Talk**

## Multiple impactors on Asteroid Vesta: noble gas and nitrogen study in the grain separates of Lohawat howardite

**Ramakant Mahajan, Amit Basu Sarbadhikari, M. S. Sisodia**

*Physical Research Laboratory, India*

The regolith of differentiated asteroid Vesta is expected to be a mixture of many components such as primary crustal rocks, remnants of impactors, impact generated melt rocks and volcanically derived magmatic materials. We have studied Lohawat howardite, separated from the Vestan surface at ~40 Ma, to assess the various components based on noble gas and nitrogen isotopic compositions. We separated different components of the Lohawat meteorite sample that included coarse mono-mineral crystals of pyroxenes and feldspars, spherules, and impact melts. We analyzed these separates together with matrix, and bulk sample of Lohawat for isotopes of helium, neon, argon, krypton, xenon and nitrogen by stepwise heating method. Determination of noble gases and nitrogen was done simultaneously on the same aliquot. The results show that primordial (Q, HL) and solar wind (SW) trapped gases are present in the grains. Remnants of the impactors, and adsorption and injections of gas (released gas during impact melting) along with the solar wind implantation, were the sources of primordial noble gases in the Lohawat grains. The solar component observed in the spherules indicates their exposure to the solar wind, whereas the primordial noble gases were probably acquired from the impactors and/or from remnants of the impactors. Solar wind in diogenitic and eucritic grains of Lohawat supports their residence within the upper most layers of the regolith. Trapped nitrogen in the Lohawat grains includes non-solar nitrogen and solar wind. We infer that there were multiple impactors on the Vestan surface of the types of CM, CV, H, L and LL chondrites.

Talk

## Hf/W implications for an old Moon

**Maxwell Marzban Thiemens**[1], **Peter Sprung**[1,2], **Raúl O.C. Fonseca**[1], **Felipe P. Leitzke**[3], **Carsten Münker**[1]

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Understanding how planets formed in the early solar system is one of the most fundamental tasks of planetology. The Moon itself acts as a palimpsest which provides insights into when and how the Earth formed. Timing the Moon's formation divides scientists into two broad camps, one which favours an "old" Moon, (ca. 50 million years after solar system formation) while the other calls for a "young" Moon (older than 100 million after solar system formation). Key to these arguments is the observation of an excess of $^{182}W$ found in lunar samples compared to their modern terrestrial counterparts. The idea holds that a "late veneer" of material deposited after planetary formation would have deposited far less material on the Moon than the Earth, and that its inherited signature of unradiogenic W would thus overwrite the previous values.

To investigate this W signature and its origins, we combined recent experimental silicate-melt partitioning data with high-precision isotope dilution concentration analyses of W, Th, U, and high field strength elements on a large suite of lunar samples. Our results indicate that the Hf/W ratio of the lunar mantle (minimum 30) is higher than that of the bulk silicate Earth (Hf/W of 25.8). The results of our study imply that the $^{182}W$ excess is the result from in situ radiogenic ingrowth. These results lend credence to the idea of an "old" Moon, and greatly diminish the need for a late veneer to explain the Moon's unique signatures.

Poster

## P zoning in olivine in type IIA chondrules: record of a complex magmatic history?

**Lidia Pittarello**, **Theodoros Ntaflos**

*Department of Lithospheric Research, University of Vienna, Austria*

A fragment of the Argentinian L5 ordinary chondrite Nicolás Levalle (NL) has been selected for detailed investigation on P zoning in olivine, following the preliminary work by Rönick et al. (2012). The chemical classification of the fragment resulted to be L/LL (Fa 25.8±0.3 olivine and Fs 22.3±0.3 low-Ca pyroxene), but the low amount of metal suggests LL. Despite the relatively large number of preserved chondrules, the strong chemical equilibration and the occurrence of crystalline plagioclase indicate a high petrologic type.

McKibbin et al. (2013) in pallasite and McCanta et al. (2016) in ordinary chondrites postulated that P zoning in olivine retains information on olivine crystallisation history that survives thermal metamorphism, due to the slow diffusion rate of P. Incorporation of P, which substitutes Si in the tetrahedra, can occur only for fast crystallisation of olivine from a P-rich melt (Grant and Kohn 2013).

In NL, P almost exclusively appears in type IIA chondrules, and P distribution within olivine grains exhibits a variety of patterns, including oscillatory zoning, enrichment in the core, and enrichment in the rim. These patterns are unrelated to the distribution of any other minor or trace elements, which are overall equilibrated, except locally Cr. P-rich and P-free olivine crystals, as well as the different zoning styles are randomly distributed within the same chondrule. Some olivine crystals in the chondrules are rimmed by P-bearing (up to 0.3 wt%), low-Ca pyroxene, which is in contact with the mesostasis, where apatite crystallised. This suggests peritectic cristallisation of low-Ca pyroxene in the system $MgO-SiO_2$, recorded and preserved from equilibration through thermal metamorphism by P partitioning in olivine, pyroxene, and groundmass. According to Villeneuve et al. (2015), type IA chondrules might be the precursor material for type IIA chondrule, which formed by re-melting and fast crystallisation under high oxidative conditions. Constraining the magmatic history of this type of chondrules through the local distribution of P between olivine and matrix might help in better understanding type IIA chondrule formation.

References

Grant and Kohn 2013 Am Min 98:1860-1869
McCanta et al. 2016 MAPS 51:520-546
McKibbin et al. 2013 GCA 119:1-17
Rönick et al. 2011 MAPS 46:A201
Villeneuve et al. 2015 GCA 160:277-305

Talk

## Iron Oxidation State of Amorphous Silicates and Functional Chemistry of Organic Matter in the Pristine Carbonaceous Chondrite Maribo

**Christian Vollmer**[1], **Jan Leitner**[2], **Demie Kepaptsoglou**[3], **Quentin M. Ramasse**[3], **Peter Hoppe**[2]

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Mighei-type (CM) carbonaceous chondrites have recorded complex aqueous alteration processes on their parent body. Investigations of the weakly altered members of this meteorite group are of particular importance to disentangle variable alteration modes. The Maribo

CM chondrite was collected shortly after its observed fall in Denmark [Haack et al. 2009]. Its bulk oxygen isotopic composition ($\Delta^{17}O$ = -3.85‰) plots towards the less altered end of the CM suite, close to the pristine CM Paris ($\Delta^{17}O$ = -3.39‰) [e.g., Leroux et al. 2015]. Here we have initiated an electron microscopy study of matrix and organic matter (OM) in Maribo.

The C- and N-isotopic compositions of Maribo matrix were studied by NanoSIMS [Leitner et al. 2017]. Specific mineral assemblages were prepared for TEM by FIB. Brightfield and high resolution imaging was performed with a ThermoFisher “Themis” (300kV), electron energy loss spectra (EELS) at the Fe-L edge were analyzed with a Zeiss Libra (200kV) [Hopp&Vollmer 2017], and EELS of $^{15}N$-anomalous OM were acquired with a Nion UltraSTEM 100MC (60kV).

The majority of Maribo matrix within the FIB lamellae studied here consists of coarse-grained Fe-rich phyllosilicates intermingled with fine-grained areas of “spongy” nano-phyllosilicates. Within the Fe-poorer, fibrous regions, small patches of amorphous silicate material (ASM) occur. $Fe^{3+}/Fe_{total}$ ratios of several ASM regions range from 0.68 to 0.83 (mean 0.72 ± 0.05). This is higher than measured by synchrotron analyses on bulk CM chondrites [Beck et al. 2012], but within the range observed for CR/Acfer 094 matrices [Le Guillou et al. 2015; Hopp&Vollmer 2017]. This indicates that Maribo ASM has recorded a similar degree of hydration as the most primitive chondrite matrices.

A minor fraction of Maribo OM shows $^{15}N$-depleted compositions ($\delta^{15}N_{air}$ ~ -200‰) occurring as submicron organic aggregates. In the TEM, this OM is dispersed as small particles within the matrix. C-K edge functional chemistry is dominated by the typical ~285 eV onset indicative of aromatic rings as well as ketone/carbonyl, aliphatic, and carboxyl functional groups with varying intensity on the nm scale, which has been observed in CR and IDP organics as well [Vollmer et al. 2014]. In contrast to OM in CRs, which often exhibits a globular, well-defined texture (probably due to fluid reactions), this morphological and chemical small-scale variability may attest to a more pristine nature of the Maribo OM.

*The DFG is acknowledged for funding this project within the SPP 1833, and Addi Bischoff for providing the Maribo thin section.*

# 1b) Tracing life through deep time: New approaches & fresh perspectives

Talk

## Diagnosis features for Interplay of microbial mats shrinkage and growth: An actualistic approach for biosignatures in rock record and Earth's early biosphere

**El Hafid Bouougri[1], Hubertus Porada[2]**

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Since more than three-billions years, Earth's ecosystem was dominated by microbes and microbial mats thought to have flourished in a wide variety of environments. In sedimentary deposits and rocks related to cold seeps and hydrothermal vents, evidence of such interactions are preserved at a range of scales and settings, from molecular remains to thick microbial buildups, and from continental to deep sea basins. Microbial mat related structures are produced on mat surface and at subsurface settings during the life-cycle of microbial communities from growth to decay. Deciphering the biotic origin of some unusual structures preserved in Archean and Proterozoic siliciclastic and carbonate successions remains a challenge and need similar counterparts in modern microbial mats systems. Among the key structures are those produced by the interaction of mat growth and mat shrinkage (MGS), preserved on bedding surfaces and in thin to thick multilayered deposits. The modern coastal microbial mat systems in both siliciclastic and carbonate evaporitic setting yield a set of structures produced during such interaction. Two main types are distinguished according to the thickness of mat layers. In thin mats, the structures developed in the top millimeters of the mat vary considerably from simple lenticular to curved, subcircular, tri-radiate and polygonal forms. The cracks margins are upturned and may become involute or curled, and subsequently overgrown and biostabilised by a new mat. In the rock record, a similar diversity of sand-filled cracks is preserved on bedding surface and in thin biolaminated layers. They are considered as evidence of microbial mat-related thriving in a shallow peritidal environment. In thick biolaminated deposits located in shallow ponded areas of the intertidal zone, large polygons display margins with complex structures developed during continuous processes of repeated upturning and overgrowth, associated with subsequent desiccation. Similar counterparts were observed in Proterozoic laminated deposits and constitute, together with their microfabric, an evidence for a biosedimentary accretion and biolaminated deposits in peritidal setting. In both cases of thin mono-layered and thick multi-layered mats, the resulting structures constitute and interesting diagnostic feature for evidence of microbial communities in rock record and for early life adaptation to clastic and carbonate substrtate.

Talk

## Crustal weathering at the mineral:microbe interface: The effects of localised $O_2$ whiffs and altered pH

**Michelle Martine Gehringer[1], Achim Herrmann[1], Eva Stueeken[2]**

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The Great Oxygenation Event (GOE) is the period during which the level of free $O_2$ in the Earth's atmosphere rose from zero to above ~ $10^{-5}$ times that of today. Early traces of oxygen have been observed in the rock record and phylogenetic studies suggest that oxygenic photosynthesis was already in operation well before the GOE. One of the major limitations to the spread of early cyanobacteria is thought to be the limitation of essential trace metals and phosphates in the environment. It is known that pseudomats of modern descendants of ancient cyanobacteria could maintain levels of oxygen equal to present day atmospheric $O_2$ levels. What effect these enhanced levels of $O_2$ induce at the microbe mineral interface is poorly studied. Our study investigated the effects of 2 different mineral substrates on the growth of *Chroococcidiopsis thermalis* and a terrestrial nitrogen fixing *Nostoc* species.

Cultures were inoculated into flasks containing either quartz sand or basalt at present atmospheric levels (PAL) and at elevated $CO_2$ atmospheres of 2000 ppm $CO_2$. The growth curve was assessed by regular assessment of protein and chlorophyll content with the pH being determined at each sampling point. Cultures of *Chroococidiopsis* showed elevated pH levels up to pH9,5 in controls and cultures grown in the presence of quartz sand at both atmospheres tested. In contrast, *Nostoc* cultures grown at PAL conditions with basalt showed a reduction of 1 pH value. At elevated $CO_2$ levels both *Nostoc* cultures exhibited reduced pH readings down to 4,5. All cultures grown at elevated $CO_2$ exhibited higher delta $^{13}C$ fractionation, and contained more glycogen, with little change in delta $^{15}N$ values. The media had free no nitrates nor phosphates at the end of the study. However, basalt generated pseudomats were healthier, with quartz sand pseudomats dying off after 3 months. Pseudomats of both cyanobacterial strains appeared to produce higher amounts of EPS at elevated $CO_2$.

This study demonstrated that growing *Nostoc* under nitrogen free conditions, in the presence of basalt, caused a reduction in media pH sufficient to induce the dissolution of the silicate matrix. This may be due to the production of organic acids, possibly resulting from increased photosynthetic activity. The release of essential phosphates and trace elements, such as molybdenum, at the mineral microbe interface may have been sufficient to allow the expansion of cyanobacteria, and the resultant increases in atmospheric oxygen observed during the GOE.

Talk

## The Paleoarchean sulfur cycle and the increasing influence of microbial sulfur oxidation

**Sami Nabhan**[1], **Johanna Marin-Carbonne**[2], **Christoph Heubeck**[1]

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During the Archean, ocean-water sulfate levels were low due to low oxygen levels. However, sparse marine barite deposits (3.55 – 3.25 Ga old) show that sulfate formation occasionally took place already in the Paleoarchean. The S-isotopic composition of this barite with negative $\Delta^{33}S$ values shows that atmospheric photo-oxidation was a major sulfate source at this time. The S-isotopic composition of pyrite within the barite beds shows that microbial sulfate reduction (MSR) was already an active microbial pathway during the formation of the oldest barite deposit (ca. 3.55 Ga). However, the impact of microbial sulfur oxidation (MSO) on the S-isotopic composition of resulting species can easily be masked in a large homogenized pool like the Archean ocean. Therefore, we focused on the ca. 3.22 Ga old paleosols of the Moodies Group in the Barberton Greenstone Belt, southern Africa, which contain in places rock-forming, silicified former gypsum and barite nodules with preserved anhydrite and barite inclusions. The clearly terrestrial context and the variable occurrence of anhydrite, barite and pyrite within different paleosol beds caused by variations of sulfate concentrations allows to track major and minor S-isotopic variations caused by MSR and by MSO.

Moodies paleosols containing anhydrite and barite inclusions in approximately even portions reflect medium sulfate levels. Their $\delta^{34}S$ compositions of ca. 3‰ resemble those of Paleoarchean marine barite and thus presumably reflect the isotopic composition of Archean ocean-water sulfate. Paleosol beds dominated by anhydrite inclusions also contain pedogenic pyrite and reflect high sulfate levels. Both minerals display about the same $\Delta^{33}S$ values of ca. -0.2‰ and show a mass-dependent fractionation of $\delta^{34}S_{sulfate}$ - $\delta^{34}S_{sulfide}$ of up to ~34‰ due to MSR. However, paleosol beds that contain only barite reflect low sulfate levels and have a $\delta^{34}S$ composition as light as -1 with partly positive $\Delta^{33}S$ values. Such a composition is unique for Archean sulfate and can only be explained by the oxidation of $\Delta^{33}S$-positive sulfur either due to the presence of oxygen or from MSO but the presence of detrital and pedogenic pyrite and the lack of oxidized iron minerals favor MSO. The consequences of MSO on the S-isotopic composition of the Moodies sulfate may thus explain the steady $\Delta^{33}S$ increase of Paleoarchean sulfates over a period of ca. 330 Ma. Indicating that MSO was an active microbial pathway since the formation of the oldest known barite deposits (3.55 Ga).

Talk

## Tracing photic zone euxinia through time—implications from organic biomarker taphonomy

**Manuel Reinhardt**[1,2], **Jan-Peter Duda**[2,3], **Martin Blumenberg**[4], **Christian Ostertag-Henning**[4], **Joachim Reitner**[2,3], **Christine Heim**[2], **Volker Thiel**[2]

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The chemistry of Precambrian oceans is a matter of ongoing debate (euxinic vs. ferruginous). Nonetheless, it is commonly accepted that conditions may have been favorable for planktonic green sulfur bacteria due to recurring photic zone euxinia. Hydrocarbon biomarkers derived from the polyunsaturated carotenoid pigment isorenieratene may provide powerful tools to trace these anoxygenic phototrophs through Earth's history. However, a robust interpretation is hampered by the limited knowledge about the taphonomic pathways controlling the fate of isorenieratene and its diagenetic products.

We tackled this problem by investigating isorenieratene derivatives in syngenetic bitumens and kerogens from two temporarily euxinic palaeoenvironments, the Bächental oil shale and the Posidonia Shale (Early Jurassic). We found that isorenieratene derivatives are only abundant in the bitumens, while being virtually absent in the kerogens, as revealed by catalytic hydropyrolysis (HyPy) and closed system pyrolysis in gold capsules (Reinhardt et al., 2018). This indicates an inefficient sequestration of these compounds into kerogen and shows that cross-linking via sulfur bonds (as it would be expected in euxinic environments) was not effective in these cases.

Our data indicate that the taphonomic fate of isorenieratene is largely controlled by (i) fast cyclization/aromatization reactions stimulated by polyunsaturation of the precursor, (ii) hydrogenation processes, and (iii) sulfide removal via anoxygenic photosynthesis and pyrite formation (Reinhardt et al., 2018). The observations made for the Bächental and Posidonia Shale kerogens provide fundamental implications for the geological record of carotenoid biomarkers, particularly in iron-rich palaeoenvironments (such as the Proterozoic ocean). A rapid sequestration of the polyunsaturated precursors into kerogen has been considered crucial for preserving these biomarkers over large geological timescales. Our study demonstrates that such incorporation may not always occur. The observed peculiar taphonomy may rather represent an alternative mechanism preserving highly functionalized aromatic carotenoids without kerogen sequestration.

References

Reinhardt, M., Duda, J.-P., Blumenberg, M., Ostertag-Henning, C., Reitner, J., Heim, C., Thiel, V. (2018): The taphonomic fate of isorenieratene in Lower Jurassic shales—controlled by iron?. *Geobiology*, *16*, 237–251. https://doi.org/10.1111/gbi.12284

Talk

## Biological methane production under putative Enceladus-like conditions

**Simon K.-M. R. Rittmann**

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The growth conditions of methanogens are to a certain extent compatible with environmental conditions on extraterrestrial bodies throughout the Solar System, in particular to Mars and icy moons (e.g. Europa and Enceladus). Furthermore, the detection of silica-rich dust particles, as an indication for ongoing hydrothermal activity, and the presence of water and organic molecules in the plume of Enceladus, have made Saturn's icy moon a hot spot in the search for potential extraterrestrial life in the Solar System.

Low temperature serpentinization reactions are assumed to occur on Enceladus. These reactions produce strongly reducing and highly alkaline fluids, and molecular hydrogen ($H_2$) and methane ($CH_4$), which can be used as an energy source by chemosynthetic life. Moreover, serpentinite-hosted ecosystems are potential sites where life may first have evolved on Earth. Kinetic and thermodynamic computations of low-temperature serpentinization indicate that there may be sufficient $H_2$ gas production on Enceladus to serve as a substrate for abiogenic, but possibly also for biological $CH_4$ production.

Among all known microbes capable of thriving under extreme and, therefore, potentially extraterrestrial environmental conditions, methanogens from the domain Archaea are intriguing organisms. This is due to their broad metabolic versatility, enormous diversity, and ability to grow under extreme environmental conditions. Methanogens are among the organisms that could potentially thrive under the predicted conditions on Enceladus, considering that both $H_2$ and methane $CH_4$ have been detected in the plume. *Methanothermococcus okinawensis* was tested under the physicochemical conditions extrapolated for Enceladus – 50 bar, gaseous inhibitors, and liquid inhibitors. The findings indicate that methanogens from Earth could potentially grow and produce $CH_4$ under putative Enceladus-like conditions. Moreover, some of the $CH_4$ detected in the plume of Enceladus might, in principle, be produced by methanogens.

Biomarkers, e.g. lipids as an indirect sign for past or present life on other celestial bodies also became an important tool in Astrobiology. Therefore, a comprehensive evaluation of the core lipid composition of *M. okinawensis* was performed to analyse how and in what extent the settings in our experiments impact its composition. It was found that *M. okinawensis* modifies the absolute number of diether and tetraether lipids when cultivated under putative Enceladus-like conditions. Future space missions to icy moons would need to consider that the lipid composition of methanogens could vary. Other biomarkers, such as nickel, patterns of low molecular weight hydrocarbons, or carbon isotopes, might facilitate in searching for signs of autotrophic hydogenotrophic methanogenic life.

Poster

## The reconstruction of microbial habitats during Mesoproterozoic stromatolite formation

**Sebastian Viehmann[1], Simon V. Hohl[2], Dennis Krämer[3], Michael Bau[3], Detlef H.G. Walde[4], Stephen J.G. Galer[5], Shao-Yong Jiang[6], Patrick Meister[1]**

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Ancient stromatolites mainly consist of authigenic carbonate which may have formed within living microbial mats and, hence, provide unique archives of local physico-biogeochemical conditions within the mats and of the prevailing water chemistry of the paleo-depositional environment. In this study we report trace element and Cd isotope data of individual mesobands of Late Mesoproterozoic domal stromatolites and conophyta from the Paranoá Group (Brazil).

Carbonate leachates of domal stromatolites show rather flat shale-normalized REY patterns (subscript SN) with slightly positive $Y_{SN}$ anomalies indicating that the carbonate was formed in a very restricted environment dominated by terrigenous REY from the continental hinterland. In contrast, conical *conophyta* with typical seawater-like $REY_{SN}$ patterns formed in a milieu dominated by open ocean seawater. The lack of positive $Eu_{SN}$ anomalies suggests that the (sea)water present at both locations was not significantly influenced by high-temperature, hydrothermal fluids, while negative $Ce_{SN}$ anomalies indicate slightly oxidizing conditions in the atmosphere-hydrosphere system during the Late Mesoproterozoic.

In combination with redox-sensitive trace elements such as Ce, Mn and U, the additional analysed $\varepsilon^{112/110}Cd$ values can be used to clearly distinguish between two carbonate endmembers that formed at the seawater-microbial mat interface and the interior of the ancient microbial mat, respectively. Hence, the geochemical reconstruction of stromatolite environment suggests that REY geochemistry in stromatolite-associated carbonate is a reliable proxy to reconstruct the physico-chemical conditions in Precambrian microbial habitats and further highlights Cd isotopes as novel geochemical proxy to gather unique insights into microbial habitats and element cycling on Early Earth.

# 1c) Evolution of the Early Earth's mantle-crust and ocean-atmosphere systems

Poster

## Tracing the onset of oxidative weathering with uranium isotopes

**Annika Brüske[1], Stefan Weyer[1], Gueluem Albut[2], Stefan Schuth[1], Ronny Schoenberg[2], Nic Beukes[3], Axel Hofmann[3], Thomas Nägler[4]**

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The invention of photosynthesis, was a key moment in Earth history, initiating major changes in the evolution of the oceans, atmosphere and life. An increasing number of studies provide evidence that enhanced oxygen levels in the atmosphere and upper oceans already existed before the Paleoproterozoic Great Oxidation Event (GOE), likely generated by photosynthesis [1][2]. However, the spatial and temporal increase in atmospheric oxygen levels and whether it was directly linked to the onset of photosynthetic oxygenation, is highly debated. Here, we present U isotope data from black shales, carbonates and iron-rich sedimentary rocks that were deposited between 3.2 to 2.2 Ga ago. Uranium (U) is a redox-sensitive trace metal whose redox changes induce characteristic isotope fractionations that may be preserved in the rock record. The analysed samples comprise mainly drill core and some outcrop samples from the Barberton (3.23 to 3.15 Ga) and Transvaal Supergroups (Ghaap and Chuniesport Groups, 2.58 to 2.52 Ga; Pretoria Group 2.42 to 2.25 Ga) in South Africa. Sub-recent U mobilisation was monitored by simultaneous analyses of $\delta^{234}U$, and detrital contribution was monitored with Th/U and Al/U. Only those samples with significant U enrichment ($U_{EF}$ > 2, relative to average continental crust) were considered. They show variations in authigenic $\delta^{238}U$ ranging from -0.83 to 0.05 ‰, which significantly excel the typical $\delta^{238}U$ range of the continental crust (-0.2 to -0.4 ‰). Remarkably, we observed a significant increase in $\delta^{238}U$ variability from samples of the Ghaap Group and those of the Pretoria Group (Duitschland Formation). The predominantly light U isotope composition of the latter samples may best be explained by the onset of partial mobilisation of U, associated to the onset of oxidative weathering of uraninite, just before the GOE. This weathering induced U mobilization would likely result in a preferential mobilisation of $^{235}U$, resulting in predominantly light U isotope compositions in oceanic sediments. Light $\delta^{238}U$ values were not observed in the overlying Timeball Hill Formation, deposited after the GOE, which may indicate the onset of essentially quantitative weathering of uraninite and other U-bearing minerals, as a result of more enhanced atmospheric oxygen levels.

[1] Kendall et al. (2013) Chem. Geology 362, 105 – 114.

[2] Wille et al. (2007) GCA 71, 2417 – 2435.

Talk

## Archean geodynamics and the onset of plate tectonics

**Vinciane Debaille[1], Camille Francois[2], Emmanuelle Javaux[2], Craig O'Neill[3], Alan D. Brandon[4]**

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Since the Archean (between 4 to 2.5 Gyr ago) was much hotter than the present time because of higher rates of internal heat production, it is traditionally accepted that the mantle was convecting faster, resulting in faster mixing time and also plates at the surface of the Earth moving faster. Short-lived isotope systems are particularly adapted to understand the geological processes that occurred during the Archean because their production stopped at some point in the past and only mixing can subsequently modify them. As such, the system $^{146}Sm$-$^{142}Nd$ where $^{146}Sm$ was extinct ~0.5 Gyr after the formation of the solar system is particularly useful to investigate the Earth's early geodynamics.

By using this system, we found a resolvable positive anomaly of $\mu^{142}Nd = +7 \pm 3$ ppm in a 2.7 Gyr old tholeiitic lava flow from the Abitibi Greenstone Belt indicating that early mantle heterogeneities formed between 4 and 4.5 Gyr persisted ~1.8 Gyr after Earth's formation [1]. This result contradicts the expected rapid early (~0.1 Gyr) [2, 3], as well as the slower recent (~1 Gyr) mixing rates in the convecting mantle [3-5]. We developed a numerical modelling [1, 6] that suggests that inefficient convective mixing can occur even in a highly convective mantle in absence of plate tectonics, i.e. in a stagnant-lid regime. Our model allows only sporadic and short subduction episodes throughout the Hadean and Archean in order to explain the long-term preservation of chemical anomalies in a highly convective mantle. Modern subduction is characterized by (U)HP-LT metamorphism eclogite-facies rocks. Eclogites are absent from the Archean record, hence corroborating the absence of modern-style subduction zones. On the other hand, we will also present the oldest evidence of HP-LT eclogite at 2.1 Gyr from the Congo craton, which is a clear indicator that the 2.7-2.1 Gyr period was a turning point for the onset of modern plate tectonics on Earth [7].

References:

[1] Debaille, et al. (2013), *Earth Planet. Sci. Lett.*, **373**, 83-92. [2] van Keken and Zhong (1999), *Earth Planet. Sci. Lett.*, **171** 533-547. [3]

Coltice and Schmalzl (2006), *Geophys. Res. Lett.*, **33**, L23304. [4] Kellogg and Turcotte (1990), *J. Geoph. Res.*, **95**, 421-432. [5] Allègre, et al. (1995), *Geophys. Res. Lett.*, **22**, 2325-2328. [6] O'Neill, et al. (2013), *American Journal of Science*, **313**, 912-932. [7] François, et al. submitted.

**Poster**

## Hafnium and Nd isotope systematics of Pilbara basalts and komatiites from the Pilbara craton, Australia: tracing changes of Archean mantle composition through time

**Eric Hasenstab[1], Vera Schmitt[1], Christian Marien[1], Jonas Tusch[1], Martin van Kranendonk[2], Kathrin Schneider[3], Elis Hoffmann[3], Carsten Münker[1]**

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The compositional characteristics of ancient mafic to ultramafic successions allows inferences on the evolution of Earth's mantle through time. In order to better constrain the depletion history of the Archean mantle, 21 pristine mafic samples from the Pilbara Craton in NW Australia were investigated for their Hf and Nd isotope and trace element composition. The sample suites studied in this work can be divided into two distinct volcanic associations: (1) the oldest units (Warrawoona Group, Kelly Group, Roebourne Group, Soanesville Group and Dalton Suite; 3525 - 3180 Ma) show flat to slightly LREE depleted trace element patterns that are mostly attributed to plume volcanism [1], and (2) the younger units (Whundo Group, Croydon Group and Fortescue Group; 3120 – 2772 Ma), with more diverse trace element patterns and significant LREE enrichments, indicating that the sources of these rocks were overprinted by an enriched components.

Because the investigated samples have preserved pristine magmatic features and coherent major vs. trace element trends, Hf and Nd isotope data of these rocks are regarded as being sufficiently robust to determine the depletion history of their mantle sources. Values of εHf(t) and εNd(t) are both slightly superchondritic and span a narrow range that varies from 0 to +3.2 and +0.3 to +2.0, respectively. Although the samples cover a wide age range from 3525 Ma to 2775 Ma, the younger samples do not show increasingly radiogenic Hf or Nd compositions, as would be expected for an isolated depleted mantle. Rather, εHf(t) and εNd(t) stay constant over this time interval of nearly one billion years. This observation might be explained by a mixture of depleted and primitive mantle domains where increasingly radiogenic initial Hf and Nd isotope signatures in the depleted domains are buffered by an influx of more primitive mantle material. In order to test this scenario, we conducted trace element modeling which suggests that melts from the oldest samples were derived from a mixture of a primitive mantle domain and a long-term depleted domain in almost equal proportions. In addition the overall trend displayed by most samples, somewhat lower εHf(t) and εNd(t) are observed in some samples that also display markedly higher $Gd/Yb_{CN}$, La/Yb and the lower Nb/Nb*. This observation suggests that these samples might have been affected by small amounts of so previously unrecognized crustal assimilation involving pre-3.5 Ga felsic basement.

[1] Smithies, R. H., et al. (2005) *Earth Planet. Sci. Lett.* **238,** 284–297.

**Talk**

## The ICDP BASE Project: Barberton Archean Surface Environments

**Christoph Heubeck[1], BASE Team[2]**

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We report on a submitted ICDP Full Proposal with the objective to drill sedimentary rocks of the Early Archean Barberton Greenstone Belt, South Africa. Sedimentary (and minor volcanic) units of the Moodies Group (~3.22 Ga, ~3.7 km thick) were deposited within ~1-14 Ma and thus record Archean surface processes in fluvial to prodeltaic depositional environments at very high resolution. Despite tight regional folding, metamorphic grade is only lower greenschist-facies; widespread early-diagenetic silicification preserved abundant micro- and macrotextures virtually without strain. Moodies strata allow the regional and temporal contextualization of high-resolution analytical data, equal or superior to Pilbara strata. They record numerous bio-geo-atmo-hydrosphere interactions and are ideal to investigate Archean terrestrial-marine transitions, particularly those related to diverse microbial life. These "earth system" and "global environmental change" topics provide an excellent match to the themes of a nascent UNESCO world heritage site in the Barberton Mountain Land.

We conducted a field workshop in October 2017 in which 48 scientists from 11 countries participated. We inspected, discussed and prioritized potential sections. Four focus groups (life, paleoenvironment, "hard rock", and sedimentation dynamics) defined eight inclined drillholes of 300-600m length each, targeting transitions between thick tidal microbial mats, fluvial and coastal gypsiferous paleosols, shoreline systems, delta complexes, potentially eolian strata, and prodeltaic jaspilites and banded-iron formation.

Principal questions include:

(1) Is there a stratigraphic rhythmicity preserved in the fine-grained prodelta sediments ? What is the origin of its clay minerals ? How do coastal BIFs and jaspilites relate to nearby tidal microbial mats ?

(2) What is the ecology, 3-D morphology and metabolism(s) of the abundant (oxygenic photosynthetic ?) microbial mats in minimally compacted tidal-facies sandstones ? What is their C-isotope microstratigraphy, preservation pathway(s), origin of early diagenetic chert, and the degree of thermal overprint ? Can we constrain net O2 production rates and the early N cycle ?

(3) What global surface conditions can be inferred? What was the redox state (sulfate, redox-sensitive metal isotopes), temperature and composition of ocean water and of early diagenetic fluids, and the relevance and processes of weathering and early diagenesis by paleosols formation ?

(4) What does the paleomagnetic record imply about the strength of the Earth's magnetic field ?

(5) What is the association between a thick mid-section lava and Moodies basin collapse ? Can high-precision U-Pb dating of air-fall tuffs quantify rates of sedimentation and subsidence on a permobile lithosphere dominated by vertically-dominated tectonics ?

**Talk**

## Hf-Nd-Os isotopic and trace element constraints on the magmatic history of the ca. 3.46 Ga Dwalile greenstone remnant, Swaziland

**J. Elis Hoffmann[1], Emmanuel Musese[2], Patrick Ganz[1], Alfred Kröner[3,4], Carsten Münker[2]**

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The ca. 3.46 Ga Dwalile greenstone remnant (DGR) represents the largest and best-preserved supracrustal assemblage within the 3.2-3.66 Ga Ancient Gneiss Complex (AGC) in Swaziland. The package consists of amphibolites, ultramafic rocks and felsic volcanic sheets as well as metasediments comprising metagreywacke, metaquartzite, Banded Iron Formation and metapelites. The DGR is intruded by 3.46-3.44 Ga TTG-type granitoids. Based on whole-rock Nd isotopes, a previous study proposed that the mafic-ultramafic rocks were crustally contaminated. More than 3.5 Ga old detrital zircons in metasediments reveal the presence of older felsic AGC crust during deposition of these rock.

We measured the whole-rock Hf-Nd-Os isotope compositions as well as major and trace elements. Moreover, we dated granitoids as well as felsic volcanic rocks by U-Pb on zircons using SHRIMP II. In addition, the Hf-in-zircon isotope compositions of felsic volcanic rocks were measured. The Hf-Nd-Os isotope measurements reveal that some samples were disturbed during post-depositional metamorphism, and some samples were crustally contaminated as reflected by age regression lines that are about 100 Ma too old. The whole-rock Sm-Nd system was least disturbed and little influenced by crustal contamination, preserving perfect isochron relationships that agree with the zircon ages of the felsic metavolcanic rocks. The whole-rock Hf-Nd isotope compositions of least contaminated samples are $eHf_{3.46}$ ~+3.5 and $eNd_{3.46}$ = +1.2, indicating a depleted mantle signature. First Re-Os isotope measurements indicate crustal contamination, but yielded Os isotopic compositions close to the primitive mantle value at 3.46 Ga. The trace element patterns of amphibolites show an imprint of crustal contamination, whereas most ultramafic rocks are flat or depleted in LREE.

Surprisingly, the U-Pb zircon ages of intrusive granitoid gneiss sheets are similar to those for the felsic volcanic layers that were deposited under submarine conditions between pillow basalts, metasediments and volcanic flows. This is best explained by fast vertical movements of crust, possibly induced by repeated lower crustal delamination events leading to burial and fast isostatic uplift.

**Talk**

## Why are hypozonal orogenic gold deposits restricted to Precambrian orogens?

**Jochen Kolb[1], Annika Dziggel[2]**

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Hypozonal orogenic gold deposits formed at 500-700°C and 2-7 kbar in syn- to post-peak metamorphic shear zones, at an apparent geothermal gradient of 40-80°C/km, which is similar to mesozonal orogenic gold deposits. Hypozonal orogenic gold deposits appear to be restricted to the Precambrian and they formed between ca. 3030 Ma (New Consort, Barberton Greenstone Belt, South Africa) and ca. 550 Ma (Navachab, Damara Orogen, Namibia). The PT conditions of orogenic gold formation define a linear trend in PT space, resembling terrane exhumation. The PT conditions of hypozonal orogenic gold deposits lie largely below the wet granite solidus, but always below the wet solidus of their host rock, and in the 1-phase stability field for aqueous-carbonic ore fluid compositions.

Phanerozoic mesozonal orogenic gold deposits formed predominantly in external accretionary orogens with only a few and smaller examples in collisional orogens. The orogenic gold deposits in external orogens are hosted by shear zone-controlled veins in accreted oceanic and island arc terranes, where gold mineralization is < 10 million years younger than the host rocks. Hypozonal orogenic gold deposits are hosted by strike-slip shear zones separating greenstone belts from granite-gneiss terranes or in normal shear zones around metamorphic core complexes. Others are hosted by reverse shear zones close to major terrane boundaries, locally associated with a jump in metamorphic grade. Hypozonal orogenic gold deposits postdate the age of their host rocks by 40-100 million years, indicating a different tectonic setting. The regional geological evolution shows that the hypozonal gold mineralization formed in the centre or hinterland of Precambrian orogens during the collision stage in either an accretionary or a collisional orogen, when the terranes are uplifted. The important factors are the regional PTD evolution forming inverted or condensed metamorphic gradients in a dynamic orogeny after collision or accretion, where hydrothermal fluids can be generated by metamorphic processes and channelled into shear zones.

A possible explanation for the lack of Phanerozoic hypozonal orogenic gold deposits is a different thermal regime of the Precambrian crust, where higher metamorphic grades are reached at higher crustal levels, which however did not result in fundamentally different orogenic processes. This may be supported by increasingly faster exhumation rates of high-grade metamorphic rocks in Neoarchean orogens that are explained by increasingly stiffer and colder crust, which can support a significant amount of crustal thickening similar to that observed in modern orogens.

**Talk**

## Pristine $^{87}Sr/^{86}Sr$ isotope compositions of Paleo- and Mesoarchean seawater inferred from carbonate interstitials in pillow lavas from the Pilbara Craton, Western Australia

**Chris S. Marien[1], Sebastian Viehmann[2], Axel Gerdes[3], Jonas Tusch[1], Martin Julian van Kranendonk[4], Carsten Münker[1]**

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Carbonate rocks may serve as reliable archives for Precambrian seawater, but are rare in early Archean greenstone belts, thus hampering reconstructions of early Archean seawater compositions. Amongst these rare carbonate occurrences are apparently primary interstitial carbonates within pillow lavas that are important remnants allowing to reconstruct the composition of ancient oceans and the atmosphere [1]. However, carbonates are highly susceptible to secondary alteration and therefore, metamorphic, diagenetic, and hydrothermal post-depositional events may mask the pristine geochemical signature of the ancient fluids from which carbonates precipitated.

In order to discriminate between these different effects and gather information about Early Archean seawater chemistry, we employed a combined approach including conventional Rb-Sr isotope measurements by MC-ICPMS at the University of Cologne, high spatial resolution measurements by LA-ICPMS at the University of Frankfurt, and trace element measurements at the University of Vienna. Here, we present first Sr isotope data for 16 carbonate interstitials, cavity fillings, and veins of covering the Euro, Apex, Mt. Ada, Honeyeater and Whundo mafic units (3.5 – 3.1 Ga) in the Pilbara craton in Western Australia. Diluted acetic acid leachates from the carbonates reveal that five microcrystalline calcites (Euro, 3.35 Ga; Whundo Group, 3.13 Ga) exhibit markedly low $^{87}Sr/^{86}Sr_t$ isotope compositions (0.7010 to 0.7013) and high Sr concentrations of >900 ppm. In contrast, coarse grained carbonates exhibit lower Sr concentrations (20 – 260 ppm), combined with more radiogenic $^{87}Sr/^{86}Sr_t$ between 0.7023 up to 0.7159. Most carbonates show typical REY (rare earths and yttrium) distributions of Archean seawater, even though the concentration are a magnitude higher than in near-contemporaneous stromatolites [2].

In agreement with earlier publications (e.g. [2, 3]) our data suggests that the Archean seawater composition at 3.35 Ga is influenced by terrestrial weathering. Previous suggestions (e.g. [4]) of a mantle buffered ocean until 2.7 Ga can be ruled out. Riverine runoff in the Mesoarchean lead generally to slightly elevated $^{87}Sr/^{86}Sr$ values of 0.7010 to 0.7013 and are therefore significantly higher than the proposed mantle value of 0.70051 [5] at the same age.

[1] Schidlowski et al. (1975) *Precamb. Res.* **2**, 1-69

[2] Van Kranendonk et al. (2003) *Geobiology* **1**, 91-108

[3] Satkoski et al. (2016) *EPSL* **454**, 28-35

[4] Shields & Veizer (2002) *G3* **6**, 1-12

[5] McCulloch (1994) *EPSL* **126**, 1-13

**Talk**

## >2.74 Ga meteoric waters recorded in triple O isotope compositions of metamorphic peridotites

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Peridotites from the Ivnartivaq area, SE Greenland, have unusually low $\delta^{18}O$ down to ~1 ‰ that are potentially explained if these rocks have interacted with meteoric waters (Peters et al. 2017). To better understand how the O isotope signal of meteoric waters was incorporated in the peridotites, we have studied the trace element concentrations and mineral compositions of these rocks. Selective enrichments in fluid-mobile elements (Rb, Pb, Li) and fractionated Y/Ho up to 36 g/g relative to MORB in the bulk rocks, as well as unusually high forsterite contents of up to 96.5 mol % in olivine coupled with variable Ni contents suggest that the peridotites formed via deserpentinisation of a hydrated ultramafic protolith. The O isotope signal of meteoric waters in the peridotites was thus probably inherited from a serpentinite protolith. U-Pb dating of zircon in a crosscutting tonalite dike through the peridotite lens gives a concordant age of ~2.787 Ga with possible granulite facies overprint at ~2.74 Ga, i.e. in good agreement with the evidence for granulite facies conditions in the granitoids of the surrounding Kuummiut terrane around this time. We suggest that this age corresponds to the age of protolith deserpentinisation and therefore represents a minimum age for the meteoric waters that are recorded in the peridotites.

There are three major implications to this conclusion. First, sufficient degrees of Rayleigh distillation must have occurred in the hydrological cycle >2.74 Ga ago to have produced meteoric waters with $\delta^{18}O$ ~ -13 ‰. Secondly, surface temperatures in the Archean must have been moderate to cold for at least a period of few thousands of years. Third, the peridotites from Ivnartivaq must have formed in a tectonic setting in which meteoric waters could have interacted with ultramafic rocks. Selective depletions in Ba, Sr and Eu relative to the primitive mantle in the bulk rocks suggest that the ultramafic protoliths of the peridotites had formed as cumulates of mafic magmas, i.e. siilat to the peridotites studied by Szilas et al. (2015). We therefore speculate that the peridotites formed in an Iceland-type setting in which melting of thick packages of mafic crust had produced sufficient volumes of granitoid crust to rise above sea level. In conjunction with the rifting that is associated with such a setting, the meteoric waters could have then penetrated the granitoids through faults and reached the ultramafic cumulates at depth.

**Poster**

## High precision triple oxygen isotope study of a Mesoarchean Banded Iron Formation of the Pongola Supergroup, South Africa

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Decreasing $\delta^{18}O$ of chemical sediments with increasing age suggests that the early oceans were either very hot [1] or the $\delta^{18}O$ of seawater was very low [2]. It is also possible that the sediments themselves are diagenetically altered [3]. We performed petrographical and geochemical studies on iron-rich and silica-rich layers from outcrop samples from the Mesoarchean Sinqeni Iron-Formation, Pongola Supergroup, in the valley of the White-Mfolozi River, South Africa, to address this issue.

On the basis of Fe and Si concentrations we extrapolated triple oxygen isotope compositions of the mineral endmembers of different BIF layers to $\delta'^{18}O^{quartz} = 16.0 \pm 1.6$ ‰ and $\Delta'^{17}O^{quartz} = -102 \pm 11$ ppm and $\delta'^{18}O^{ironoxide} = -11 \pm 6$ ‰, $\Delta'^{17}O^{iron\ oxide} = -22 \pm 23$ ppm. The silica end member has a composition that is identical to Archean cherts from various other localities. The chemical composition, mineralogy and compositional variability of the Fe oxide layers reflect post-depositional alteration. The triple isotope data show that silica and Fe oxides cannot have been in equilibrium at any T. We suggest that the oxygen isotope composition of the chert reflects a primary signature, whereas the Fe oxides have undergone massive post-depositional alteration. For the most altered Fe (and Mn) oxides, meteoric water has been identified as alteration fluid.

The chert data are discussed with respect to the composition and temperatures of Archean oceans and with respect to diagenetic processes.

[1] Knauth and Epstein (1976) GCA 40, 1095–1108.

[2] Perry (1967) EPSL3, 62–66.

[3] Degens and Epstein (1962) Bull. Am. Assoc. Petrol. Geo. 46, 534-542.

**Talk**

## Tungsten isotope systematics in rocks from the Pilbara Craton, Australia

**Jonas Tusch**[1], **Mike Jansen**[1], **Chris S. Marien**[1], **Eric Hasenstab**[1], **Martin V. Kranendonk**[2], **Carsten Münker**[1]

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Recent analytical improvements have revealed the presence of small $^{182}W$ isotope anomalies in terrestrial rocks ranging in age from the Archean [e.g.1-2] to Phanerozoic [e.g. 3-4]. Both, excesses [1,4] and deficits of $^{182}W$ [2,3], respectively, have been found. The $^{182}W$ isotope anomalies are vestiges of ancient chemical heterogeneities that have been preserved in Earth's mantle. Incomplete addition of late veneer or early silicate differentiation are the two preferred explanations for the $^{182}W$ anomalies. A straigthforward interpretation of $^{182}W$ anomalies, however, is often hampered by disturbed elemental W patterns that are often affected by secondary W enrichments in altered rocks [e.g. 2,5].

Here, we present the first comprehensive high-precision $^{182}W$ isotope dataset for mafic Archean rocks from the Pilbara Craton, NW Australia, that is one of the best preserved early Archean successions on Earth. Our set of samples covers all major mafic units of the Pilbara Supergroup. All samples were initially screened for W-alteration by isotope dilution measurements of high field strength elements (HFSE), U, and Th. Only those samples were further considered that exhibit primary W abundances, as reflected by canonical W/Th ratios. All measured samples from the Pilbara Supergroup exhibit positive $^{182}W$ excesses ranging in $m^{182}W$ from +6 to +14ppm with uncertainties generally better than ±5 ppm (95% conf. limit). Samples from the Warrawoona Group are indistinguishable with a mean excess of +9.4 ± 2.6 ppm (95% conf. limit), significantly lower than previously reported [6]. At present, the origin of the $^{182}W$ isotope anomalies in the Pilbara Craton cannot unambiguously be resolved. However, independent evidence for older depleted mantle domains is provided by consistently superchondritic ε Hf(t) and ε Nd(t), ranging from 0 to +3.2 and +0.3 to +2.0, respectively.

[1] Willbold et al. (2011) *Nature* **477**, 195-198. [2] Puchtel et al. (2016) *G³* **17**, 2168-2193. [3] Mundl et al. (2017) *Science* **356**, 66-69. [4] Rizo et al. (2016) *Science* **352**, 809-8012. [5] Tusch et al. (2017) *Goldschmidt 2017*. [6] Archer et al. (2017) *Goldschmidt 2017*.

**Talk**

## Earth's oldest mantle peridotites may originate from a supra-subduction zone setting

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Remnants of Archaean mantle are scarce, yet, direct measurements of Eoarchean mantle rocks can provide important information on geodynamic processes operating on early Earth. Therefore, >3.8 Ga old mantle peridotites from the Itsaq Gneiss Complex (IGC) of southern West Greenland were investigated in terms of their petrology and geochemistry. The sample set includes well preserved mantle peridotites from the region south of the Isua Supracrustal belt (Isukasia terrane) and from the Narssaq ultramafic body, south of Nuuk (Færingehavn terrane). Here we present whole rock trace element and Lu-Hf isotope data and, in addition, Lu-Hf isotopic data that were obtained from mineral separates (olivine, orthopyroxene and amphibole) of selected samples.

Nearly flat primitive mantle-normalized REE patterns of the mantle peridotites resemble those of refertilized modern abyssal peridotites and may reflect re-enrichment processes by a melt-like subduction component as also indicated by Th-REE-HFSE characteristics. Based on a simple evolution-model for the investigated mantle rocks, we suggest depletion by hydrous partial melting in the spinel stability field, followed by subsequent addition of low quantities of an adakitic melts, similar to modern slab-derived melts and to Archean slab melts.

The Lu-Hf isotope measurements of whole rock and mineral separates indicate only minor disturbance of the Lu-Hf system in most of the peridotites. Whole rock and whole rock – mineral age regression lines mainly yield Eoarchean ages, in agreement with minimum ages inferred from dated crosscutting tonalite sheets (e.g., Friend et al., 2002). The well preserved peridotites, including mantle rocks, have positive $\varepsilon Hf_{(3.81)}$ ranging from +0.6 to +5.6. Considering the re-enriched trace element patterns of the peridotites, the spread in Lu-Hf isotope signatures most likely represents a mixture between refractory mantle and the enriching components. Hence, the Lu-Hf ages most likely represent the time of re-enrichment of the mantle sources by slab melts. As they overlap with Eoarchaean Re-depletion model ages (van de Löcht et al. 2018), depletion and re-enrichment processes likely occurred at very similar times.

Friend, C.R.L., Bennett, V.C., Nutman, A.P. (2002) Abyssal peridotites >3800 Ma from southern West Greenland: Field relationships, petrography, geochronology, whole-rock and mineral chemistry of dunite and harzburgite inclusions in the Itsaq Gneiss Complex: Contributions to Mineralogy and Petrology, 143, 71–92.

van de Löcht, J., Hoffmann, J.E., Li, C., Wang, Z., Becker, H., Rosing, M.T., Kleinschrodt, R., Münker, C. (2018) Earth's oldest mantle peridotites show entire record of late accretion. Geology, 46, 199–202.

# Topic 2: 50 years of plate tectonics

## 2a) InterRidge: Multidisciplinary research on oceanic ridges

Poster

### The Foundation-PAR plume-ridge interaction: constraints on competing forces and the structure of oceanic lithosphere

**Philipp A. Brandl**[1], **Christoph Beier**[2], **Lars H. Rüpke**[1], **Karsten M. Haase**[2], **Colin W. Devey**[1], **Marcel Regelous**[2], **Folkmar Hauff**[1]

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Actively upwelling mantle plumes can affect the physical and chemical properties of nearby mid-ocean ridges even over large distances by supplying additional material and heat to the axes. Strong plumes affecting several hundreds of kilometers of the ridges close to Iceland or Galápagos lead to large scale excess melting with the formation of oceanic plateaux or islands and long sections of thickened crust at the adjacent spreading centers. The Foundation plume – Pacific-Antarctic Ridge (PAR) interaction is different in that the fast-spreading ridge effectively masks most geophysical signals of the melting anomaly. Here, we demonstrate that the well-preserved geochemical signature allows to set precise constraints on the geodynamics of plume-ridge interaction.

Compositionally, plume-ridge interaction leads to the enrichment of the axial magmas in radiogenic isotopes and incompatible elements. In order to qualitatively map out the spatial distribution of plume material underneath the PAR, we applied robust statistical fitting methods to geophysical and geochemical data of the axis. In agreement with the geophysical constraints on plume center location, the highest $^{206}Pb/^{204}Pb$ and La/Sm Ba/Nb and Nb/Zr ratios occur in axial lavas near 37.5°N. From this point, the geochemical plume signature decreases north- and southwards along the axis. To the south, the geochemical plume signature is detectable for >250 km but to the north the plume signature is bound by the overlapping spreading centre (OSC) at 36.5°S, restricting the dispersal of plume material northwards to within ~100 km off the plume center.

Here, we show that the lithosphere structure of the PAR controls the dispersal of plume material along the axis, at least at present. The small offset in lithosphere thickness at the retreating limb of the OSC prevents plume material to flow further north. This implies, that plume material must be channeled into the ridge axis and dispersed along the axis at very shallow, sub-lithospheric, depth. Otherwise, plume material would be expected to be tapped also by lavas erupted on the PAR segment further north that is in parts closer to the plume center than much of the Foundation Segment. The preferred along-axis flow of plume material towards the south may be enhanced by the plate configuration that imposes a southward drag of material at sub-axial asthenospheric depths. This system, however, is not in a steady-state but responds to the competing forces between the ridge and plume with the Foundation plume showing evidence for increased activity at a periodicity of ~1.5 Ma.

Talk

### Oceanic core complexes: Evolution, nature of corrugated faults, and interactions between tectonic extension and mass-asting processes

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Oceanic core complexes (OCCs) are commonly found along slow-and ultras-slow spreading ridges. These structures often display a characteristically corrugated fault surface exposed at the seafloor, whose origin and nature has not been constrained to date. Oceanic accretion is also directly linked to the formation of OCCs, that are likely shaping the internal structure and composition of the oceanic lithosphere; in portions of the northern Mid Atlantic Ridge, OCC-related accretion can account for ~50% of the lithosphere. Recently acquired near-bottom bathymetry using an AUV, together with sampling and extensive in situ observations using and ROV, has revealed key aspects of the evolution of these structures, their mode of emplacement at the seafloor. Initial fault stages are characterized by mass wasting of high-angle faults, that ceases due to back-tilt with the continued extension and the associated flexural rotation, leading to the emergence of the corrugated fault surface at the seafloor. Corrugations are generated over a thick fault zone (>>100 m), and correspond to bodies of fault rock material that are elongated in the spreading direction, and bound by a network of anostomosing fault planes, as confirmed by the presence of fault planes with sub-horizontal striations on the flanks of the corrugations. Due to trag, the detachment fault uplifts material from the hangingwall, that forms a thin wedge over it, and that decouples from the fault along a valley or moat, ~10 m deep, that is continuous laterally. Along this moat rubble and sediments from this wedge are shed onto the detachment, blanketing it almost completely. This moat and associated wedge are a common feature of active detachments, mapped in recent years with AUVs.

These results demonstrate that mass wasting processes operate from the initiation of faulting, resulting in scarp degradation, and throughout the life of detachments, with the drag of rubble covering the fault plane with continued extension. Depending on the erosion and mass wasting rates relative to tectonic extension, detachment faults may be either fully covered by material dragged from the hangingwall, or eroded by mass wasting if the emergence angle of the fault were elevated. It is thus likely that corrugated surfaces provide a very partial view of detachment faulting in the lithosphere, and that this mode of extension may be more widespread than previously thought. The pass wasting and rubble deposition also indicate that in situ observations are required to study these structures, as dredging wills ample in priority rubble cover.

**Poster**

## Major, trace element and Sr-Nd-Hf-Pb isotopic compositions of basalts from the southern Central Indian Ridge and the Rodrigues Triple Junction

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Mid-Ocean Ridges are becoming of great interest regarding the potential of polymetallic and massive sulfide ore deposits. The German INDEX research program (Indian Ocean Exploration for Seafloor Massive Sulfide) investigates the southern Central Indian Ridge (CIR) including the Rodriguez Triple Junction (25.6°S; RTJ). This ridge isintermediate to slow-spreading rates, causing complex petrogenetic processes and exhumation of deep oceanic lithosphere such as ultramafic rocks and gabbro. Numerous active hydrothermal systems such as Kairei (25.3°S) and Edmond (23.9°S) vent fields occur along the CIR. Here we present major, trace element and Sr-Nd-Hf-Pb(double-spike) isotope data from moderately altered to fresh basalts, microcrystalline dolerites and gabbros from on-axis RTJ and off-axis ridges (Edmond and Kairei).

Based on their geochemical data. three groups have been characterized: (1) the Kairei and plagioclase-bearing RTJ samples, together with a gabbro sample, showing an extreme depletion in the most incompatible elements (i.e. lower Th/Yb, Nb/Yb, LREE/HREE etc.) and having high εNd (~8.5), εHf (~16) and Sr isotope ratios (~0.7031), but extremely low $^{206}Pb/^{204}Pb$ (~17.4) and $^{208}Pb/^{204}Pb$ (~37.3); (2) this group contains olivine-bearing samples from the RTJ and volcanic glasses from Edmond, having the lowest Sr isotopes (~0.7029), lower εHf (~14.5) but similar εNd, and intermediate $^{206}Pb/^{204}Pb$ (~17.8); and (3) the Edmond basalts, extending to lower εNd (~8), εHf (~13) and higher Sr (~0-70306) and Pb (~18.05) isotope ratios. Group 2 and 3 have characteristic N-MORB to E-MORB trace element patterns. In plots of MgO versus major element oxides, the samples form a fan-shaped trend converging to a common high-MgO source (group 1). Group 2 has systematically higher $Na_2O$, $K_2O$, $TiO_2$ and lower CaO at a given MgO than groups 1 and 3. We propose that group 1 lavas represent a depleted mantle component with little seawater contribution. Elevated heat flow in the area of the Rodrigues Triple Junction may have triggered high degrees of melting associated with a plume-ridge interaction. Alternatively, the group 1 lavas may have been contaminated by surrounding ultramafic rocks such as mantle peridotite and gabbro. Group 3 lavas extends to slightly enriched composition, typical for Indian MORBs where group 2 is somewhat intermediate and would represent the ambient upper mantle in normal conditions.

**Talk**

## Wadi Gideah (Sumail Ophiolite, Sultanate Oman): A reference section through the lower fast-spreading oceanic crust

**Juergen Koepke**[1], **Dieter Garbe-Schönberg**[2], **Tim Mueller**[1], **Samuel Müller**[2], **Dominik Mock**[1], **Harald Strauss**[3], **Stefan Schuth**[1], **Benoit Ildefonse**[4]

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For testing models of accretion and cooling of the oceanic crust at fast-spreading ridges, a complete profile through the lower oceanic crust is necessary. In the absence of such a profile in modern oceans, we established a reference profile through the paleocrust of the Sumail Ophiolite (Oman), which is regarded as the best analogue for fast-spreading oceanic crust on land. For establishing a coherent data set, we sampled the Wadi Gideah in the Wadi-Tayin massif from the mantle section up to the basalts and performed different analytical and structural investigations on the same suite of samples. The whole sample set contains of more than 400 samples focusing on primary magmatic features in order to establish the mode of accretion of fast-spreading crust. We also systematically sampled hydrothermal fault zones, in order to characterize the cooling of the crust. The Wadi Gideah hosts the drill sites GT1A (lower crust) and GT2A (foliated / layered gabbro transition), where 400 m long cores have been drilled in the frame of the ICDP Oman Drilling Project (OmanDP). Thus, our Wadi Gideah crustal transect provides also the reference frame for these drill cores.

The evolution of major and trace elements of minerals and rocks with depth reveals a clear differentiation trend which is weak in the lowermost crust evolving significantly upward towards the gabbro/dike transition, implying in-situ crystallization in the deep and mid crust. This supports a hybrid accretion model that is characterized by sheeted sill intrusion in the lower part of the plutonic crust and gabbro glacier features in the upper section. This hybrid model is also supported by results on crystallographic preferred orientations (CPO) of the minerals within the gabbros, and by crystallization temperatures calculated from REE's in coexisting clinopyroxene and plagioclase.

A requirement for our hybrid model is significant hydrothermal cooling in the lower crust for the consumption of the latent heat of crystallization. This was facilitated by channelled hydrothermal flow zones, preserved today in faulted zones of extensively altered gabbro. These gabbros show higher $Sr^{87}/Sr^{86}$ ratios if compared to the background gabbro, the presence of late stage minerals (amphibole, oxides, orthopyroxene, apatite) and evidence for hydrous partial melting, as consequence of fluid / rock interaction at very high temperatures.

Obviously, these fault zones remained active for channelled fluid flow during the entire cooling stage of the oceanic crust down to low-temperature mineral assemblages.

Talk

## What Causes the Layering of Gabbros? – A Microanalytical and Microstructural Investigation on the Layering of two Gabbro Sections in the Oman Ophiolite

**Dominik Mock[1], Benoit Ildefonse[2], Dieter Garbe-Schönberg[3], Samuel Müller[3], Kathrin Faak[4], Olivier Namur[1], Jürgen Koepke[1]**

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As a part of the lower oceanic crust, layered gabbros form the largest coherent body of layered cumulates on our planet. Nonetheless, their formation mechanisms are still unclear. This study investigates two small-scale profiles from the layered gabbro section of the Oman Ophiolite showing modal layering of Cretacous oceanic crust formed at a fast-spreading mid-ocean ridge. It combines petrological, geochemical and microstructural methods and provides an unprecedented amount of high-resolution data for the investigation of layer-forming processes in the lower oceanic crust.

Layering is observed at the dm scale in profile 1 (Wadi Samrah) and at the mm scale in profile 2 (Wadi Wariah). Olivine Mg#s ((Mg/Mg+Fe) * 100; molar basis) of 78 to 80 in Wadi Samrah and 84 to 87 in Wadi Wariah are consistent with a lower stratigraphic height of profile 2 and indicate crystallization of both profiles from a primitive melt. Laser ablation analyses reveal slight zoning in clinoypoxene in terms of rare earth element distribution. The calcium-in-olivine geospeedometer indicates cooling rates between 2.8 and 4.9 °C/kyr for profile 1 and 100 to 320 °C/kyr for profile 2. The low misorientation in crystallographic preferred orientations (CPO) of plagioclase and clinopyroxene and higher misorientation in CPO of olivine indicates that magmatic deformation dominated compared to plastic deformation.

Major element contents of olivine, clinopyroxene and plagioclase show distinctive changes in magma composition at a particular layer in profile 1. This is best observed for Mg# in both olivine and clinopyroxene and $TiO_2$ in clinopyroxene. Changes in petrology seem to correlate with changes in CPO which have been quantified using J- and BA-indices. Both, petrological and microstructural changes can be explained by magma replenishment which can be responsible for the formation of modal layering. Crystal settling is a common process in magma chambers and potentially leads to the formation of cyclical layering. It is also consistent with our data from profile 1. In contrast, the mm-scaled layering in profile 2 can be well explained with the idea of crystal aging [1]. Furthermore, the step changes in chemical composition within profile 2 indicates that injection of more primitive melt also played a role in formation of this layered profile.

[1] Boudreau, A. E. (1995). Crystal aging and the formation of fine-scale igneous layering. *Mineralogy and Petrology*, *54*(1-2), 55-69.

Talk

## Mass transfer at hydrothermal fault zones in the lower oceanic crust: An example from Wadi Gideah, Samail ophiolite, Oman

**Samuel J. Müller[1], Barbara Zihlmann[2], Dieter Garbe-Schönberg[1], Damon A.H. Teagle[2], Jürgen Koepke[3]**

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Hydrothermal circulation and alteration within the oceanic crust are critical processes for the exchange of mass and heat between the solid earth and the oceans. Although there is good knowledge about how and where shallow hydrothermal circulation occurs, there remain significant shortcomings in our understanding about the geometry and intensity of deep hydrothermal circulation through the lower oceanic crust, as these systems cannot be examined in-situ at active ridges.

Here we present a petrographic and geochemical field study of a hydrothermal fault zone located within the deep layered gabbro section of the Cretaceous Samail ophiolite. Field observations reveal a one-meter thick normal fault comprising weakly foliated chlorite±epidote rocks with disseminated pyrite and chalcopyrite, which surround heavily altered gabbro clasts. This fault zone offsets a coherent series of layered gabbros and is oriented subparallel to the sheeted dikes that crop out to the south of Wadi Gideah. Gabbro in both hanging and footwall of the fault is altered and abundantly veined. As inferred by experimental studies[1] and petrographic observations sea water related hydrothermal alteration of gabbro follows two reactions: (I) clinopyroxene+fluid => tremolite±actinolite, and (II) clinopyroxene+plagioclase+fluid => chlorite. Epidote if present, is partially growing into open cavities. Chlorite thermometry reveals formation temperatures of about 275°C within the walls and roughly +50°C more in the fault rock. The late stage of alteration mainly forms prehnite and laumontite, mostly along veins.

Whole rock mass-balance calculations reveal strong depletion of alkali elements (Li,Na,Rb,Cs) for all altered rock types. Ni,Cr,Sc and light rare earth elements (LREE) get leached from the layered gabbro. Mn,Co and Fe are leached as well but precipitated into the fault rock which additionally shows a considerable gain in Zn,Cu, and U, pointing towards a strongly charged, reactive fluid composition. The formation of hydrous phases leads to a pronounced increase of water within all fault related lithologies. Based on silica loss and solubility the intensity of alteration requires a fluid-to-rock mass ratio of 450:1 to 900:1.

Strontium isotope whole rock data of the fault rock yield $^{87}Sr/^{86}Sr$ ratios of ~0.7046, which is considerably more radiogenic than fresh layered gabbro from this locality ($^{87}Sr/^{86}Sr$=0.7030–0.7034), and similar to black smoker hydrothermal signatures based on epidote, measured in Wadi Tayin. Altered gabbro clasts within the fault zone show comparable values with $^{87}Sr/^{86}Sr$ ratios of ~0.7045–0.7050, whereas hanging wall and footwall display values only slightly more radiogenic than fresh layered gabbro.

[1] Beermann et al.,(2017),GCA,197,167–192.

Poster

## Virtual 3D-Deposit model and resource estimation of a Seafloor Massive Sulfide deposit at the Mid-Atlantic Ridge

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Because of the challenging technical conditions in the deep sea, the database of seafloor massive sulfide (SMS) deposits is scarce and drill hole data and geophysical measurements are complex and costly, particularly if compared to land-based exploration. In the recently completed EU FP7 project "Blue Mining", a virtual SMS deposit cluster was generated consisting of 30 deposits ranging from 0.3 Mt to 5.4 Mt in size, with an overall tonnage of 40 Mt to be exploited within 20 years. The virtual deposits are located within a band of 25 km along the Mid Atlantic Ridge (MAR), with 12.5 km of oceanic crust on each side of the active spreading axis. The individual deposits are on average 100 km apart. Out of this virtual cluster, one deposit was chosen as the reference case for the 3D deposit model, using the spatial distribution of metal grades, lithologies and geometries of a drilled deposit, "Solwara 1" from offshore PNG and explored by Nautilus Minerals Inc., as a template. To adjust the metal grades to a MAR system, average grades from the Trans-Atlantic Geotraverse (TAG) at the MAR were combined with publicly available drill hole sample data from Nautilus. Each of the sample data of copper, zinc, gold and silver from Solwara 1 was multiplied with a factor, preserving the geometry, volume and distribution of the original deposit. Finally, a resource estimation was made for the virtual model, which can be used as predictive base for deep sea mine planning.

Talk

## Boron systematics of vent fluids from peridotite-hosted hydrothermal systems

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Hydrothermal vent systems hosted in peridotites are common along slow spreading mid-ocean ridge axis. Nevertheless, the impact of water-rock interaction in these systems on the boron concentrations and boron isotopic composition ($\delta^{11}B$) of the discharging fluids were not studied so far. There are differences in the behavior of boron (B) during alteration of basalt (concentrations decrease in rock) and peridotite (concentrations increase in rock). Hence, studies of vent fluids from peridotite hosted systems are needed to gain better constraints of overall hydrothermal exchange fluxes. Also, B systematics of vent fluids may be a useful tracer of basement lithology along the flow paths of hydrothermal solutions.

We investigated B concentrations and $\delta^{11}B$ compositions of vent fluids from four hydrothermal systems (Logatchev, Ashadze II, Irinovskoe and Semenov-2) that are associated with oceanic core complexes along the Mid-Atlantic ridge spreading center between the 15´20°N and the Marathon Fracture Zones. All vent systems are situated in peridotite, but magmatic influences were suggested to affect vent fluids in the Semenov hydrothermal area (Melekestseva et al., Mar. Geol. 349, 37-54, 2014). The vent fluids were collected with gas-tight fluid samplers using ROV MARUM Quest 4000 during cruise M126 of R/V Meteor. The fluid end-member compositions (re-calculated to zero magnesium) of all four hydrothermal systems are depleted in B and $\delta^{11}B$ relative to bottom seawater and show B contents between 191 to 290 µmol/kg and $\delta^{11}B$ values between 33.5 to 36.6 ‰. These observations point to a preferential uptake of B by the underlying basement, which becomes preferentially enriched in $^{11}B$. These changes are most likely associated with the serpentinization of ultramafic lithologies that appear to be the dominant rock type in the sub-seafloor at all four sites.

Talk

## KNIPAS – exploring active seafloor spreading processes at segment-scale

**Vera Schlindwein**[1], **Frank Krüger**[2], **Florian Schmid**[1], **Mechita Schmidt-Aursch**[1], **Wojciech Czuba**[3], **Tomasz Janik**[3]

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Knipovich Ridge passive seismic experiment (KNIPAS) is a state-of-the-art seismological project that studies on segment scale the active spreading processes of an ultraslow mid-ocean ridge. The generation of new ocean floor is accompanied by characteristic seismicity that reflects ongoing spreading events and the physical state of the young lithosphere, and differs widely depending on spreading rate.

While fast spreading ridges hardly show earthquakes that are large enough to be recorded on land, magmatic spreading events at the slowest spreading centres seem to be regularly preceded by earthquakes larger than M 5. The depth limit of earthquakes and their presence and absence reveal along-axis variations in the thermal and mechanical regime of the lithosphere. Therefore, it is necessary to record earthquakes locally with ocean bottom seismometers (OBS). Such surveys, however, typically have limited spatial extent and cannot reveal segment-scale spreading processes like along-axis melt flow, while spatially more extended data sets of hydro-acoustically recorded earthquakes yield no information on focal depth and can therefore not constrain lithospheric thickness or temperature.

The project KNIPAS instrumented for the first time an entire ridge segment with OBS. During Polarstern cruise PS100 in July-September 2016 we deployed 23 OBS of the German Instrument Pool for Amphibian Seismology (DEPAS) along a 160 km long ridge section that covers Logachev Seamount and a neighbouring volcanic centre. An additional 3 OBS of the Institute of Geophysics, Polish Academy of Sciences, were deployed around Logachev Seamount. The instruments recorded seismicity until July-October 2017 depending on capacity. Cruise MSM67 of Maria S. Merian acquired wide-angle seismic profiles across Logachev Seamount and the subsequent cruise MSM68 successfully recovered all OBS.

We now have a comprehensive seismological dataset at hand that will contain despite partly high noise levels in the vicinity of Logachev volcano an expected 9000 earthquakes M>1 and several dozens of well-recorded teleseismic events to study spatial variations of seismicity, thermal structure and lithospheric thickness of an ultraslow spreading ridge. In a joint project we will combine the expertise of our work groups to study seismicity pattern, analyse the large-scale lithospheric structure with modern passive seismic methods to be adapted for the special conditions of marine seismic surveys and to image at high resolution the structure of a volcanic centre.

Talk

## Hydrothermal plumes and δ³He anomalies above the Southern Mid-Atlantic Ridge (13°-33°S) indicating previously unknown active vent sites

**Florian Schmid[1], Maike Peters[2,3], Maren Walter[1,2], Jürgen Sültenfuß[2], Colin Devey[4]**

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The Mid-Atlantic Ridge south of 13° S was entirely unexplored for hydrothermal activity until recently. In 2013 the expedition MSM-25 of the German research vessel Maria S. Merian set sail to systematically survey the axial region of the Southern Mid-Atlantic Ridge between 13° and 33° S for signs of active hydrothermal venting. Our shipboard sampling gear during the expedition included a typical conductivity-temperature-depth (CTD) probe with an additional turbidity sensor mounted to carousel water sampler and miniaturized plume recorders which were attached to the cable above the CTD system. Turbidity and oxidation-reduction-potential sensors were also mounted to the GEOMAR Abyss, the autonomous underwater vehicle (AUV) operated during the cruise. We intensely surveyed and sampled the water column above 16 separate ridge segments by conducting 65 CTD stations (including single dip casts and tow-yo stations) and 11 successful AUV dives. A total of 973 water samples collected at CTD stations for noble gas analysis were filled in gas-tight glass ampoules or copper tubes and later analysed for their isotopic composition in the Bremen helium isotope lab. About 800 of the samples were successfully analysed and yield meaningful $\delta^3$He results. Thus, we achieved a unique dataset of $\delta^3$He concentrations above the Southern Mid-Atlantic Ridge which is likely unprecedented in its extent along the spreading axis and density of sampling in particular in the bottom waters filling the axial rift valley. In summary, we identified 10 discrete plumes that are characterized by anomalies either in turbidity, oxidation-reduction-potential, $\delta^3$He or most frequently a combination of these parameters. Eight of the plume anomalies were previously unknown. Most of the identified hydrothermal plumes are located above the high-relief segment centres, where the axial morphology indicated robust magmatism. This contribution will give an overview of the hydrothermal plume discoveries made during the MSM-25 expedition which certainly represent promising targets for further exploration of active venting along the Southern Mid-Atlantic Ridge.

Poster

## Peridotite-fluid-microbe interaction in the oceanic lithosphere: insights from sulfur geochemistry

**Esther Martina Schwarzenbach[1], Janne Liebmann[1], Gretchen Früh-Green[2], Harald Strauss[3], Uwe Wiechert[1], Benjamin Gill[4], David Johnston[5]**

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The oceanic lithosphere is exposed to extensive water-rock interaction during and after its formation along mid-ocean ridge spreading centers. Around 25% of ocean floor formed along slow-spreading ridges comprises of serpentinized peridotite as mantle rock is tectonically exposed to seawater. Alteration of peridotite is associated with considerable chemical, physical and mineralogical transformations, and can support microbial communities due to formation of $H_2$, $CH_4$, and formate during the serpentinization reaction.

Here, we summarize and review recent approaches to resolve the alteration history of peridotite-hosted hydrothermal systems and, in particular, the links between and temporal sequence of abiogenic fluid-rock interaction and microbial activity. We use bulk rock and *in situ* sulfur isotope geochemistry, multiple sulfur ($^{32}$S, $^{33}$S, $^{34}$S) isotope compositions, and detailed petrographic examination of variably serpentinized peridotites drilled by the IODP (International Ocean Discovery Program) and ODP (Ocean Drilling Program), and samples collected in ophiolite sequences in Italy and Costa Rica. These studies show that peridotite-hosted hydrothermal systems undergo a complex alteration history with fluids of different origin; High-temperature fluids (>350°C) are recorded by positive $\delta^{34}S$ and $\Delta^{33}S$ values and are associated with Ni-, Co-, and/or Cu-rich sulfide mineral assemblages. Locally, high-T fluids also produce talc, chlorite, and amphibole-rich rocks reflecting the input of Si, Al, and Ca-rich fluids. Negative $\delta^{34}S$ values are indicative for the presence of microbial sulfate reduction supported by low temperatures of water-rock interaction, whereas seafloor weathering is documented by the presence of Fe-oxides and -hydroxides. At many locations though, high and low temperature processes overlap; Sulfide mineral intergrowths comprise *in situ* $\delta^{34}S$ values showing heterogeneities of up to 30‰ within single grains and $\Delta^{33}S$ analyses of sulfides and sulfates record distinct mixing lines between different sulfur pools. Overall, the combined application of *in situ* and bulk rock multiple sulfur isotope measurements with petrographic observations allows to resolve the different episodes of sulfur cycling during ocean lithosphere alteration and the temporal changes between abiogenic and biogenic processes that control the sulfur cycling in these systems.

**Poster**

## Hydrothermal $\delta^3He$ anomalies above slow and ultraslow spreading ridges

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Helium as an inert noble gas is a non-reactive tracer in the ocean and detectable over long distances away from individual sources. Hydrothermal fluids are the only oceanic source for primordial helium, which is characterized by its isotopic ratio. Hydrothermal fluids and hence plumes are highly enriched in helium, especially the isotope $^3He$, leading to He/Ne ratios which are higher than outside the plumes as well as an excess of $^3He$, described by the parameter $\delta^3He$ that is defined by the isotopic ratio R = $^3He/^4He$ compared to the atmospheric ratio, $R_A$ ($\delta^3He = 100[(R/R_A)-1]$, in %). This excess can be traced up to a 500.000-fold dilution by high precision detection methods. Therefore, $\delta^3He$ can be used to identify and track the output of hydrothermal sites in the near and far field. Moreover, interpreting the helium isotopic ratios in conjunction with other parameters of a site as for example other chemical species, stratification, or flow field, can provide insights into various aspects of the hydrothermal system like host rock, plumbing, or vent fluxes.

Here, we present an extensive high quality data set of O(2000) samples from slow and ultraslow spreading ridges in the Atlantic, Arctic and Southern Ocean, including two sites on the Gakkel Ridge, as well as data from several sites on the Mid-Atlantic Ridge between 16°N and 33°S, and the South-West Indian Ridge.

**Talk**

## The orientation of the paleo-subduction zone beneath the Troodos Ophiolite

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Supra-subduction zone ophiolites such as the Cretaceous Troodos Ophiolite of Cyprus are fragments of oceanic crust formed by seafloor spreading in the neighbourhood of subduction zones. Many are thought to represent fore-arc crust, created during subduction initiation, because their lava stratigraphy apparently resembles that of the fore-arc crust beneath the Izu-Bonin-Mariana arc. Here we use major and trace element analyses of fresh volcanic glasses from the Troodos ophiolite to determine the regional and temporal variation in the composition of Troodos lavas. We reconstruct the location of the former subduction zone in relation to the spreading axis by using geochemical data. We find that the Troodos Ophiolite formed by NW-SE directed spreading above an eastward-dipping subducting plate. The orientation of the spreading axis relative to the subduction zone, together with the lack of systematic temporal evolution in the composition of magmatism indicate that the Troodos Ophiolite does not represent fore-arc crust formed during subduction initiation. Our model proposes that the Troodos Ophiolite probably formed at a back-arc spreading centre that propagated into arc – fore-arc crust.

**Poster**

## MORB modified by melt-peridotite interaction at crust-mantle boundary: An experimental perspective

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The coherent cores of layered gabbros drilled by IODP Expedition 345 at the Hess Deep Rift validate the Penrose model for interpreting the structure of fast-spreading oceanic crust. One remarkable founding is the occurrence of orthopyroxene as an abundant phase in these deep-level cumulaterocks, which is however unexplainable by crystallization experiments from primary MORB melts and indicates significant modification of melt composition prior to the formation of cumulates. In this study, in combination with analysis of natural samples, we experimentally investigated the effect of melt-peridotite interaction on its modification of MORB melt composition. We performed melt/rock interaction experiments using a starting glass representing upmoving MORB melt, which is similar to the primitive MORB composition estimated based on bulk crust of Hess Deep, and a natural lherzolite representing mantle rocks. The experiments were performed at a nominally dry condition using an Internally Heated Pressure Vessels (IHPV), with temperature and pressure consistent to crust-mantle boundary. Three types of experiment were designed. The first type experiments were run at a constant temperature, which serve as pilot for investigating phase stabilities. The second type experiments were run starting from a high temperature (near liquidus) and finished at a lower temperature, in between with slow cooling rate. The third type experiments contain two separated runs, with the first run at near-liquidus temperature for efficient melt-peridotite interaction, and second run at a lower temperature for crystallization using a synthesized starting glass composition identical to the melt produced from the first run experiment. Melt-peridotite interaction experiments were in all cases performed simultaneously with equilibrium crystallization experiments using a pure primitive MORB glass, which allows easy assessment of the effect of melt-peridotite interaction. Up to now, the first and second type experiments are completed, and the third type are still under work. Our experiments show that interaction between MORB melt and peridotite can increase melt $SiO_2$ content effectively without significantly changing its MgO content, resulting in an evolving trend to orthopyroxene saturation. Particularly, in one melt-peridotite interaction experiment at 1180 °C, magmatic orthopyroxene is observed coexisting with a large proportion of melt, clearly demonstrating that orthopyroxene can be stable at an early-to-middle magmatic stage. Our experiments imply that melt-peridotite interaction at crust-mantle boundary may be a common scenario responsible for the formation of heterogeneous MORB melts, in which some are close to orthopyroxene-saturation composition and thus orthopyroxene-rich cumulates can be formed during its ascending in lower crust.

# 2b) Microfabrics, deformation mechanisms and physical properties of rocks

Talk

## Seismic anisotropy of slow-spreading oceanic crust and serpentinized mantle constrained from textures of rocks drilled at Atlantis Massif (Atlantic Ocean) during IODP Expedition 357

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Seismic tomography data suggest that slow spreading ridges have weaker seismic anisotropy of crust and uppermost mantle rocks if compared to those from fast spreading ridges. Pervasive deformation, alteration and serpentinization was observed in drillcores from the sheared top of the Atlantis Massif oceanic core complex, recently sampled during IODP Expedition 357 on the slowly spreading Mid-Atlantic Ridge. Many minerals formed during that alteration (e.g. serpentine, talc, amphibole, chlorite), however, have very strong seismic anisotropies. Their plastic deformation forms crystallographic preferred orientations (CPO), thus predicting strong rather than weak anisotropy.

We have analyzed CPO of fresh and altered gabbros by neutron diffraction using the SKAT texture goniometer at the Frank Laboratory for Neutron Physics, Dubna, Russia. This method allows measurement of large samples and is especially suitable for coarse-grained rocks. Synchrotron radiation was applied for finer grained talc schist, serpentinite and altered dolerite. Measurements were performed at the high-resolution powder diffraction beamline ID22 at the European Synchrotron Radiation Facility (ESRF), Grenoble, France. Sample cylinders with diameters of 15 mm were measured in transmission rotating the sample about 360°. Raw data from both measurement types were processed using Rietveld Texture Analysis to yield compositions and quantitative information on the CPO. From this and single crystal elastic constants whole rock seismic anisotropies were computed.

Coarse-grained gabbros show no or weak CPO of plagioclase, probably due to shape alignment by magmatic processes. The composite CPO results in seismic anisotropies of about one percent. The serpentinites studied so far have weak to moderate CPO, probably caused by lattice bending and curling of serpentine minerals. Seismic compressive wave velocity (Vp) anisotropies, however, are up to about 10 percent. Talc-amphibole-chlorite schists have pronounced CPO and resulting Vp anisotropy up to 20 percent. Hydrothermally altered dolerite has a Vp anisotropy of about 5 percent. We conclude that altered and sheared rock types are important in creating seismic anisotropy at slow-spreading oceanic ridges. Shear zone and alteration abundance in the uppermost layer of hydrated mantle could, therefore, potentially be used as proxy for seismic anisotropy and vice versa.

Poster

## The role of the feldspar solvus for deformation mechanisms and rheology of the lower crust

**Marina Kemperle, Reiner Kleinschrodt**

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The study of granulite fabrics is thought to reveal information on the rheological behaviour of the lower crust (Brown et al., 2011). However, many granulites show partial or even complete overprint according to different stages of retrogression. In line with this, observed microfabrics correspond to post-peak metamorphic amphibolite facies conditions and even lower grades. As a result, rocks altered in this way represent rather upper crustal material and, thus, rheological principles of lower crustal granulites do not fit.

In this study, we use the deformation fabrics of feldspar and quartz to reveal differences between the rheology of the lower and upper crust.

The deformation of feldspar in the transition of upper to lower crust is subject to exsolution processes due to the miscibility gap of plagioclase and alkali feldspar below 650° C (Benisek et al., 2010). The subsolvus deformation leads to recrystallization of feldspar solid solution porphyroclasts to fine-grained aggregates of chemically altered 2-phase pl–kfs layers or, with quartz mobility on grain boundaries, to 3-phase pl-kfs-qtz layers. Thehypersolvus case is characterized by deformation and recrystallization of feldspars without a compositional change of the recrystallized grains producing coarse-grained aggregates.

Unlike many other granulite terrains, the Highland Complex of Sri Lanka underwent a nearly stress-free exhumation from the lower crust (Kleinschrodt & Duyster 2002). Consequently, lower crustal structures are well preserved and only altered by grain coarsening and exsolution of feldspars developed undisturbed during very slow cooling (2-3° C/ Ma) from T ~850° C (Hölzl et al., 2001). This led to a coarse-grained recrystallization of quartz and feldspar with isolated feldspar ribbons within quartz. The latter show high aspect ratios and well developed CPOs indicating typical high-T slip systems. According to this, dislocation creep flow laws can be considered valid for quartz and feldspar in the lower crust.

We compare these features to other granulite terrains (Indian and Variscan Granulite Terrains), where stresses drastically change the granulite facies textures towards decreasing temperatures while granulite facies parageneses still persist. Grainsize and grainsize evolution seem to be key factors for the rheological behaviour of granulites, i.e. the switch between grainsize-sensitive and insensitive mechanisms (e.g. Maierova et al 2017). A combination of quartz and feldspar fabric parameters (grainsize, SPO and LPO) can be used as proxies for the rheology of middle to lower crust.

**Talk**

## Deformation microstructures and textures of quartz - new insights on old paradigms

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Quartz crystallographic preferred orientations (CPO, textures) are commonly used to deduce information about deformation kinematics, strain path and overall deformation conditions such as metamorphic grade. These inferences are based on empirical correlations between observations from deformation experiments and nature, as well as theoretical assumptions about the processes involved in texture formation. In principal, these assumptions are: (i) specific positions on c-axis pole figures are related to the activity of specific slip systems, and (ii) crystal re-orientation during deformation results from a crystal-plastic process.

EBSD-based, combined analysis of the texture and microstructure of new data allows re-evaluation of a few long standing paradigms about the relation between deformation and texture-forming processes, namely:

(a) Quartz c-axis pole figure types (e.g. a Y- or peripheral maxima) are often interpreted to relate to a specific deformation temperature. Based on new analyses (Kilian & Heilbronner, 2017) of experimentally deformed quartzite (experiments of Heilbronner & Tullis, 2006), we suggest that differential stress and strain control the CPO while temperature is rather of secondary nature.

(b) Basal<a> is regarded as a very common, and easy slip system in quartz. However, closer inspection of the experimental evidence and misorientation data obtained from naturally and experimentally deformed quartz suggests it plays a subordinate role.

(c) The so-called c-axis opening angle has been suggested as a deformation thermometer (e.g. Kruhl, 1998), although the exact nature of the temperature sensitive mechanism governing the pole figure geometry still remains unclear. It is shown that there are significant variations in the c-axis opening angle as a function of grain scale deformation and the extent of dynamic recrystallization, but that the opening angle is unrelated to temperature.

These new results have implications for our understanding of the texture-based interpretation of deformation conditions as well as opening up perspectives on the understanding of natural deformation conditions.

References:

Heilbronner, R., Tullis, J., 2006. Evolution of c-axis pole figures and grain size during dynamic recrystallization: results from experimentally sheared quartzite. J. Geophys. Res. 111, B10202.

Kilian, R. and Heilbronner, R.: Analysis of crystallographic preferred orientations of experimentally deformed Black Hills Quartzite, Solid Earth, 8, 1095-1117.

Kruhl, J.H., 1998. Reply: prism- and basal-plane parallel subgrain boundaries in quartz: a microstructural geothermobarometer. J. Metamorph. Geol. 16, 142-146.

**Poster**

## Physics and kinematics of S-C-fabric in plastic shear zones

**Falk H. Koenemann**

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The terms and concepts by which deformation is described to this day were coined in the 18$^{th}$ C. The theory was worked out by Cauchy 1827, by adapting Newton's mechanics which is energetically conservative. The Euler-Cauchy theory was written before the discovery of physical work (1829), the modern understanding of geometric space (1840-60), bonds in solids (1849), and the First Law of thermodynamics (1847) and thus the body of non-conservative physics. It is unable to describe deformation work; it cannot consider bonds, and it follows the wrong energy conservation law [1, 2]. The entire energetic thinking which developed from 1840 on, which is so fundamental for modern physics, has been ignored completely in continuum mechanics. It is a straightforward proof to show that the Cauchy stress theory is not valid. It is also well known that strain contains insufficient information to describe a deformation: from a given strain it is not possible to tell how the deformation came about. Instead, the full information is given by the displacement field. A correct approach to elastic deformation and proper understanding of stress must be based on thermodynamics, and it must deliver the displacement field as result.

These requirements are satisfied by a new deformation theory [3]. For simple shear, the stress (a force vector field) has non-orthogonal eigendirections forming the angles 101 and 79°. The *contracting eigendirection* is at 112° to the bulk shear direction, the *extending eigendirection* is at 11°. The S-plane in S-C fabrics is the 11° direction into which elongated porphyroclasts (s-clasts) are rotated. The C-plane at -28° follows the bisector of the 79° angle enclosed by the eigendirections. d-clasts are restricted to this sector only. Joints and cracks in shear zones follow accurately the contracting eigendirection at 112°, which is also the regional maximum stress direction along the San Andreas fault in California (observed at 111 ± 14. The entire set of fabric elements and kinematic indicators in shear zones is therefore completely predicted.

Energetic model calculations for pure and simple shear indicate that plastic simple shear costs 27% less energy than pure shear for identical strain. The prediction is in accord with experimental results.

[1] Koenemann FH (2008) Int J Modern Physics B **22**, 4863-4876

[2] Koenemann FH (2014) Eur J Physics **35**, 015010

[3] Koenemann FH (2008) Int J Modern Physics B **22**, 2617-2673

Poster

## Quartz textures related to exhumation of subducted continental crust: The northern range of the Vals-Scaradra Shear Zone at the front of the Adula Nappe (Central Alps, Switzerland) preliminary results

**Jacek Kossak Glowczewski, Niko Froitzheim, Ruth Keppler**

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The Adula Nappe is the structurally highest of the Lepontine Nappes in Central Switzerland and represents the distal part of the European margin, which was subducted and subsequently exhumed to upper crust levels. In contrast to over- and underlying units, the Adula Nappe experienced up to ultra-high-pressure conditions. To the north, the Adula Nappe ends in a lobe surrounded by Mesozoic metasediments. This frontal boundary of the nappe represents a discontinuity in metamorphic conditions, between higher T in the Adula Nappe and lower T outside. A shear zone with steeply dipping foliation and shallowly-plunging, WSW-ENE oriented, i.e. orogen-parallel stretching lineation overprinted the northernmost part of the Adula Nappe and the adjacent Mesozoic metasediments (Vals-Scaradra Shear Zone). It formed during the local Leis deformation phase. The Vals-Scaradra Shear Zone (VSSZ) is remarkable in that it exhibits a reversal of shear sense along strike; from sinistral in the west to dextral in the east. Quartz textures also vary along strike indicating sinistral shearing with a component of coaxial (flattening) strain in the west. The active glide systems are mostly basal- <a> and rhomb-<a>, and the recrystallization mechanism subgrain rotation, indicative of deformtion temperatures between 400 and 500 °C. In the east strong, single c-axis maxima point to dextral shearing with only minor flattening. A texture from the middle part of the shear zone is symmetric and indicates coaxial flattening.

These relations reflect complex flow within the Adula Nappe during a late stage of its exhumation. These structures indicate that the Adula basement protruded upward and northward into the surrounding metasediments, spread laterally, and expelled the metasediments in front towards west and east.

The southern border of the VSSZ is already well mapped. The actually presented field observations as well as the crystallographic preferred orientations of oriented quartz samples from the surrounding metasediments (Grava Nappe, Piz Terri-Lunchania Zone, Valser Mélanges):

1) Confirm that the VSSZ also affect the sediments outside of the Adula Nappe and help to define the northern range of its influence in addition to it.

2) Reveal the kinematics and deformation conditions in the northern part of the VSSZ and in the following help to correlate different deformation phases in front of the Adula Nappe.

We think that VSSZ is an important piece of the Adula "puzzle" and may help to better understand its tectonic evolution, especially its final exhumation to the upper-crustal level.

Poster

## Textures of phyllosilicate-bearing mud sediments indicating localized deformation in the continental wedge of the Costa Rica erosive margin

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During sedimentation and burial at continental margins, phyllosilicate-bearing sediments develop crystallographic preferred orientations (textures) controlled by the ongoing compaction as well as the size distribution and shape fabrics of the grains. Such textures can influence the deformation behavior of these sediments as well as the plate coupling and friction along the plate boundary and major faults. Phyllosilicate-bearing muddy sediments at the Middle America Trench offshore Costa Rica are affected by the subduction process in two ways: a) sediments deposited on both plates are involved into the megathrust system as it is an erosive continental margin with a small frontal accretionary prism and b) sediments from the continental wedge are overprinted by wedge-internal subduction tectonics. We collected samples of varying depths from four different drill locations across the trench retrieved during IODP (Integrated Ocean Drilling

Program) expeditions 334 and 344 as part of the Costa Rica Seismogenesis Project (CRISP). The samples from the incoming plate, the frontal prism and the slope of the upper plate were analyzed regarding the texture of the phyllosilicates in the sediments.

Sample composition is relatively similar for all sample positions across the trench in the hemipelagic section as determined by X-ray powder diffraction analysis. For texture analysis we applied synchrotron radiation at the European Synchrotron Radiation Facility in Grenoble, France, and the German Electron Synchrotron in Hamburg, Germany, as the delicate mud samples cannot be analyzed with conventional methods in wet "as-is" conditions. Phyllosilicates in samples from the incoming plate and frontal prism show in general weaker textures than the samples from the slope of the upper plate. Texture intensity does not systematically increase with depth, probably due to variable compaction and deformation, grain size and shape dependency, and large proportions of hydrated smectite. In samples from the continental wedge we can distinguish undisturbed compacted sediments from samples deformed by subduction-related tectonics, a separation that is not possible from the macroscopic core description and from microscopic investigations. Based on the admittedly incomplete sample record it can be proposed that the continental wedge is characterized by localized deformation. This is in agreement with localized faulting in an erosive continental margin. Our study shows that synchrotron diffraction is a suitable method for the texture analysis of such wet, weakly textured sedimentary mud samples.

**Poster**

## Frictional behavior of sediments in the shallow subduction channel of the erosive active continental margin offshore Costa Rica

**Robert M. Kurzawski[1], Michael Stipp[2], André R. Niemeijer[3], Delphine Charpentier[4], Jan H. Behrmann[1], Chris J. Spiers[3]**

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The Costa Rica Seismogenesis Project (CRISP) was designed to study fault zone behavior during earthquake nucleation and rupture propagation at a convergent continental margin characterized by tectonic erosion. Stage 1 drilling research (IODP Expeditions 334 and 344) focussed on composition, structure, microstructure, and physical properties of sediments and igneous rocks of the overriding and the incoming plate. The investigation of the processes causing the change from stable to unstable slip was accomplished by sampling material input at the trench and inside the wedge. The CRISP study area is located offshore Osa Peninsula (Costa Rica), where active and long-lived subduction erosion occurs along the Middle America Trench. This area is characterized by low sediment supply, fast convergence rate, abundant plate interface seismicity, and a change in subducting plate relief along strike.

The spectrum of slip modes occurring along shallow portions of the plate boundary décollement in subduction zones includes seismic, aseismic and slow slip. The factors that control the slip modes directly influence the hazard potential of subduction zones for generating large magnitude earthquakes and tsunamis. Here, we report on results from hydrothermal rotary shear experiments conducted on simulated fault gouges prepared from CRISP samples. The velocity dependence of friction was explored using all major lithologies, and covering a wide range of conditions representative for the initial stages of subduction. Temperature, effective normal stress, and pore fluid pressure were varied systematically up to 140 °C, 110 MPa and 120 MPa respectively. Sliding velocities up to 100 μm/s, relevant for earthquake rupture nucleation and slow slip, were investigated. The only sediment type that produced frictional instabilities (i.e. laboratory earthquakes) was the calcareous ooze carried by the incoming Cocos Plate, which by virtue of its slip weakening behavior is also a likely candidate for triggering slow slip events. Locking and unlocking of plate boundary megathrusts are not only related to variations in pore fluid pressure, but may also depend on the presence of pelagic carbonate-rich lithologies. Frictional instability does not require any mineral transformations, such as e.g. the smectite to illite transition, and is capable of triggering exceptionally shallow seismic events. Corresponding subduction systems fulfilling these conditions most likely occur at low-latitude as it is the case offshore Costa Rica.

**Talk**

## Geomechanical properties and structural evolution of Scaly Clay

**Ben Laurich, Werner Gräsle**

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Deformed clay rocks frequently comprise a fabric with a high density of shear zones, so-called 'Scaly Clay' (Vannucchi et al., 2003). Scaly clay is an enigmatic soft rock with important differences in rheological and hydrological behaviour compared to its more competent protolith. Developing scaly clay within or near a repository for radioactive waste bears a risk as a potential fluid pathway and as a structurally weakened zone (it disintegrates by hand).

We strive to answer where, when and how scaly clay forms and how substantial its impact on strength, stiffness and dilatancy is.

Preliminary results show that scaly clay aggregates can be produced in true-triaxial testing even at low confining pressures of 5 MPa and even in dry condition. The gained shear zone geometry resembles the natural scaly clay fabric found in the Mont Terri Rock Laboratory (cf. Laurich et al., 2017). The press is equipped with a newly invented see-through-piston that allows us to watch the evolution of shear zones and to correlate their appearance with simultaneously recorded changes in strain, withstand load and acoustic emission. We modify sequentially the sample's bedding orientation and moisture state as well as the experiment's strain rate and confining stress to test the importance of these controls on the formation of scaly clay.

During the tests, individual shear zones develop progressively, such that early shear zones define location and extend of later ones. Yet, the scaly clay in our experiments developed within a very short period (< 10s) and we currently test if saturated samples show a slower development. The results indicate a time-sensitive deformation and might provide an insight into yet unknown deformation mechanisms that act during the creep of clays.

Recently, artificial scaly clay was also studied by Orellana et al. (2018) for its geomechanical properties.

Laurich, B., Urai, J.L., Nussbaum, C., 2017. Microstructures and deformation mechanisms in Opalinus Clay: insights from scaly clay from the Main Fault in the Mont Terri Rock Laboratory (CH). Solid Earth 8, 27–44.

Orellana, L.F., Scuderi, M.M., Collettini, C., Violay, M., 2018. Do scaly clays control seismicity on faulted shale rocks? Earth and Planetary Science Letters 488, 59–67.

Vannucchi, P., Maltman, A., Bettelli, G., Clennell, B., 2003. On the nature of scaly fabric and scaly clay. Journal of Structural Geology 25, 673–688.

**Poster**

## Deformation and metasomatism of a mantle xenolith from Kimberley, Kaapvaal Craton

**Jolien Linckens, Gerhard Brey**

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In order to determine the interplay between metasomatism and deformation in the upper mantle of the Kaapvaal craton, South Africa, we combine microstructural and EBSD analyses on a deformed mantle xenolith sample from Kimberley as a first step. The sample is a garnet harzburgite that shows different stages of deformation. Most of the sample consists of olivine and orthopyroxene porphyroclasts (up to 2mm) in a fine-grained (~40 µm) olivine-rich matrix. This grain size indicates a differential stress of about 86 MPa (van der Wal et al., 1993). The olivine in the matrix shows a crystallographic preferred orientation (CPO) that suggests the activation of the (010)[001] slip system, thought to be activated at relatively high stresses and moderate-to-high water content (Karato et al., 2008). At some locations, the olivine grains in the matrix are elongated and the grain boundaries are aligned. This, in combination with the CPO, may indicate that dislocation creep accommodated by grain boundary sliding was an important deformation mechanism in the matrix. Parallel to the foliation of the matrix, a vein-like, fine-grained (~10 µm) polymineralic band occurs, with a thickness of around 400 µm. The small grain sizes indicate high differential stresses (~240 MPa; van der Wal, 1993). The band consists of olivine, orthopyroxene, interstitial clinopyroxene and few spinel grains. The olivine in this band shows no CPO. The interstitial clinopyroxene could indicate post-kinematic melt infiltration in the polymineralic band. The process by which olivine and orthopyroxene mixed in this band is unclear. Parallel to this polymineralic band, fine-grained (10 µm) orthopyroxene bands occur that often extend from orthopyroxene clasts. These bands can be extremely thin (20 µm). Some thicker (500 µm) orthopyroxene-rich bands contain remnants of orthopyroxene clasts. They are the highly deformed outer parts of orthopyroxene clasts. The foliation of the matrix and polymineralic and orthopyroxene bands is cross-cut by a later stage deformation band. Some garnets are surrounded by phlogopite crystals (up to 800 µm) and small (around 80 µm) spinel grains. The undeformed phlogopite indicates post-kinematic metasomatism by a K-rich melt.

van der Wal, D., Chopra, P., Drury, M., FitzGerald, J. 1993. Relationships between dynamically recrystallized grain size and deformation conditions in experimentally deformed olivine rocks. Geophys. Res. Lett. 20, 1479-1482

Karato S-I, Jung H, Katayama I, Skemer P. 2008. Geodynamic significance of seismic anisotropy of the upper mantle: new insights from laboratory studies. Annu. Rev. Earth Planet. Sci. 36, 59-95

**Poster**

## Microstructural observations on oxide-rich gabbros from the Atlantis Bank oceanic core complex, Southwest Indian Ridge (ODP Hole 735B)

**Luiz F. G. Morales[1], Jessica Till[2], Erik Rybacki[3]**

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Slow and ultraslow spreading mid-ocean ridges accommodate tectonic plates deformation by interplay between magmatic and tectonic processes, mainly along high angle normal faults and low angle detachment faults that characterize oceanic core complexes (OCCs). The Atlantis bank is an oceanic core complex that was exhumed by a large-scale detachment fault on the Southwest Indian Ridge. Deformation in these rocks is localized along hypersolidous and HT shear zones, later overprinted by brittle faults of different scales. Here we present the initial results of a detailed microstructural and crystallographic preferred orientation study in five samples from the oxide-rich gabbros that occur along the core. These gabbros occur with higher frequency toward the top of the section and are interpreted to have intruded the more primitive gabbros at a later stage. Composition of the studied samples varies considerably from sample to sample, between clinopyroxene and plagioclase-rich gabbros, but the content of oxides (mostly magnetite and ilmenite) is between 5-10 %. All the studied samples have well-developed foliation, but lineation is not well marked. In general, clinopyroxene occurs as porphyroclasts in the plagioclase bearing gabbros, but as discontinuous layers in the cpx-rich terms. Plagioclase occur preferentially as equigranular aggregates, whereas ilmenite, and at last extend magnetite, occur along bands parallel or oblique to the foliation. Crystallographic preferred orientation (CPO) determined via EBSD shows a weak but always present CPO for clinopyroxene, plagioclase and ilmenite. In most of the samples the clinopyroxene CPO is characterized by the alignment of poles to (100) subparallel or oblique to the pole of foliation (Z), whereas the poles of (010) or (001) are parallel to X, depending on the sample. Plagioclase CPO is characterized by the alignment of poles to (010) parallel to Z and poles to (001) close to X. Ilmenite (0001) poles are systematically aligned parallel to Z and <11-20> parallel to X. Magnetite CPO is rather weak and may either show <100> or <111> parallel to the pole of foliation. All phases show systematic peaks at low misorientation angles, in agreement with the observation of undulose extinction and subgrain boundaries. Microstructures and CPOs suggest the oxide-rich gabbros were deformed under the presence of melt (possibly with rock-melt reactions) progressively evolving to HT solid state deformation.

**Talk**

## Partial dislocations and stacking fault ribbons in deformed pyrope at high pressure and temperature: Combining ECCI and FIB milling techniques to prepare site-specific TEM samples

**Nobuyoshi Miyajima, Tommaso Mandolini, Florian Heidelbach**

*Bayerisches Geoinstitut, Universität Bayreuth, Germany*

Dislocation microstructures in experimentally deformed single crystal pyrope-rich garnet were investigated by using electron channeling contrast imaging (ECCI) and transmission electron microscopy (TEM) combined with a focused ion beam (FIB)-microsampling. In the orientation-optimized ECCI method, we successfully observed individual dislocations across subgrain boundaries in a low-atomic number mineral, pyrope-rich garnet (averaged Z-numbers, AZs ~10). In the ECCI on the single crystal garnet, polysynthetic deformation bands consisting of dislocations, unusual contrasts in stripes and inhomogeneous distributions of sub-micrometer-sized pores were found. Further site specific TEM observation on the deformation band revealed a high density of partial dislocations and stacking fault ribbons. Widely dissociated partial dislocations connected by the stacking fault ribbons might be related with low stacking fault energy in hydrous and high temperature deformation conditions of the garnet (Smith, 1982; Smith, 1985). The site-specific characterizations from ECCI to TEM, with assistance of FIB, can provide a new approach to investigate dislocation microstructures of deformed materials at high pressure and high temperature.

***References:***Smith, B.K. (1982) Deformation of Silicate Garnet; Microstructures and Experimental Rheology, Ph.D. , p. 201. University of California, Berkeley, Berkeley.

-. (1985) The Influence of Defect Crystallography on Some Properties of Orthosilicates. In A.B. Thompson, and D.C. Rubie, Eds. Metamorphic Reactions. Advances in Physical Geochemistry, 4. Springer, New York, NY.

**Talk**

## Early mantle dynamics recorded in extraterrestrial olivine fabric

**Beverley J. Tkalcec, Frank E. Brenker**

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The study of meteorites can provide nearly undisturbed insight into primary planetary processes. In addition to the magmatic and crystallisation processes revealed by mineralogic, petrologic and isotopic analysis, geologic processes that occurred during the thermal evolution of the parent body are further revealed by micro-structural analysis. Specifically, orientation fabrics record early deformation processes during cooling of the parent body and constrain the ambient conditions that prevailed at the time of deformation. This can in turn provide valuable information for the early processes that occurred during the planetary cooling of the Earth. The HED (Howardite, Eucrite, Diogenite) group of meteorites, are thought to have been ejected from the surface, the crust and the upper mantle of the differentiated asteroid, 4 Vesta [1] with olivine-rich diogenites representing material from the upper mantle. Three olivine-rich diogenites, Northwest Africa (NWA) 5784, NWA 5480 and Miller Range (MIL) 07001 were analysed in this micro-structural study using Electron Backscattered Diffraction (EBSD) to measure and visualize lattice preferred orientations (LPO) of the Vestan olivine and determine the presence (or absence) and nature of any solid-state plastic deformation. Preferred orientation was found in the olivine of all three diogenites, indicating solid-state plastic deformation [2]. The results are presented here and compared with known olivine LPOs observed in naturally deformed terrestrial peridotites or resulting from experimental deformation of synthetic olivine to determine the type of deformation endured and constrain the temperature and melt fraction prevailing at the time. We demonstrate that the observed solid-state plastic deformation was not caused by crystal settling at the base of a magma chamber crystal nor by impact-induced shock exposure. In contrast, we demonstrate that the investigated diogenites likely underwent solid-state plastic deformation in lower crustal, upper mantle shear zones as a result of dynamic movements in the Vestan mantle [3]. The results of our structural investigation of olivine-rich diogenites indicate that the solidification of the HED parent body was not a static progression, but involved large-scale dynamic mantle movements and suggests that early mantle processes within the asteroid Vesta during planetary cooling may have been more similar to those observed on Earth than previously thought.

References: [1] McSween H. Y. et al., 2011. *Space Science Reviews* 163:141–174. [2] Tkalcec B. J. & Brenker F. E., 2014. Meteoritics & Planetary Science 49:1202–1213. [3] Tkalcec et al. 2013. Nature Geoscience 6:93-97.

# 2c, e) Fifty years with plate tectonics

**Talk**

## Plate Tectonics, MOVE-ON, and models of past mantle flow

**Hans-Peter Bunge**

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50 years into the plate tectonic paradigm we have global maps of past plate motion going back 200 million years. This record of horizontal plate movement holds two important lessons for the dynamics of the deep Earth: (1) major oceanic plates in size comparable to the current Pacific plate were subducted into the Earth's mantle as deep as the Core Mantle Boundary. Their negative buoyancy induces a large scale circulation known as the plate mode of mantle flow. (2) plates change their motion on short time scales relative to the large scale mantle circulation. These changes owe primarily to a second convective mode, known as the plume mode. The plume mode also induces substantial vertical motion of the lithosphere, as modeled by Griffiths and Campbell (1990), shown by Sengor (2001) and analyzed in the stratigraphic framework of Friedrich et al. (2018). However, maps of vertical lithosphere motion related to the plume mode are still in their infancy. Such maps can be constrained from stratigraphy, basin analysis, thermochronology, landscape evolution or sediment compaction studies. Joining **M**odels and **O**bservations of **VE**rtical moti**ON** would allow us to MOVE-ON from plate tectonics, by mapping the history of 3-D lithosphere/mantle interaction. This would place powerful constraints on key parameters of geodynamic models of past mantle flow, which can be constructed now from fluid dynamic inverse theory.

**Poster**

## Ediacaran (Timanian) island arc fragments of Baltica at the north coast of Laurentia

**Solveig Estrada**[1], **Nikola Koglin**[1], **Axel Gerdes**[2], **Benita-Lisette Sonntag**[3], **Franz Tessensohn**[1]

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The Timanian Orogeny affected the northeastern margin of Baltica in Ediacaran to early Cambrian times. Rocks with Timanian ages can be found today along the circum-arctic continental margins. Their distribution provides important information for the post-Rodinia palaeogeographic reconstruction of the Arctic.

The Midtkap igneous suite in northernmost Greenland today forms isolated outcrops in early Palaeozoic deep-water sediments of the Franklinian Basin. The suite of supra-subduction zone origin is composed of intermediate and felsic intrusive rocks, serpentinite, and heterogeneous volcanic breccia (mélange). The intrusive rocks were probably exhumed by serpentinite diapirism. Intermediate intrusive rocks have Timanian zircon ages of 650–570 Ma (Rosa et al. 2016, Estrada et al. 2018). Ar–Ar biotite dating on granite (~535 Ma) together with geochemical constraints point to a duration of the island-arc magmatism until the earliest Palaeozoic. Coeval volcaniclastic detritus has also been found in the Pearya Terrane at the north coast of Ellesmere Island in the Canadian High Arctic. This composite terrane is built up by Proterozoic to Silurian meta-sedimentary and igneous rocks (subdivided into Successions 1 to 5), and amalgamated with the northern margin of Laurentia during the late Devonian to early Carboniferous Ellesmerian deformation (Trettin 1998). In Pearya, late Cambrian–early Ordovician volcaniclastic sediments of Succession 3 are almost completely derived from a Timanian volcanic arc source as indicated by detrital zircon ages (c. 560–590 Ma, peaking at around 570 Ma; Estrada et al., in press). These ages overlap the zircon age range of the Midtkap intrusive rocks. Therefore the Midtkap igneous suite and Pearya Succession 3 may have been related to the same island arc. Furthermore, serpentinite surrounding a large lens of quartz monzonite is also present in Pearya Succession 3. Serpentinite diapirism is probably a characteristic feature of the forearc of this Timanian volcanic arc. The Timanian arc was possibly split during the Caledonian Orogeny and displaced by large-scale sinistral strike-slip movements.

Estrada et al. 2018: Journal of Geodynamics. doi.org/10.1016/j.jog.2018.01.015

Estrada et al. in press: Journal of Geodynamics

Rosa et al. 2016. Precambrian Research 275, 394–405

Trettin HP 1998: Geological Survey of Canada, Bulletin 425, 108–192

**Talk**

## A comparison of lower plate structure and morphology in subduction-zone segments affected by tsunami earthquakes

**Jacob Geersen**

*GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Germany*

Since 1900 at least ten tsunami earthquakes took place in different subduction zones around the globe. These earthquakes are characterized by long source durations, a reduced component of high frequency energy, and rupture extending to the shallow plate-boundary close to the deep-sea trench. They are a threat to coastal communities and a problem for tsunami early warning as they generate larger than expected tsunamis given the surface wave magnitude of the event. Despite their often tragic consequences, we know little about the parameters that govern the occurrence of tsunami earthquakes. It remains largely unknown if they are linked to certain tectonic settings or if they can occur everywhere, independent of the regional tectonic framework. To help unrevealing the parameters that control the genesis of these unusual earthquakes I combine bathymetric and seismic reflection data from subduction-zone segments that experienced tsunami earthquakes in the 20th and the beginning of the 21st century in order to search for similarities in the structure and morphology of the subducting oceanic plate. First results indicate no correlation between the large-scale plate-tectonic configuration (age of subducting plate, convergence rate, convergence obliquity) in tsunami earthquake regions. With respect to trench sediment thickness, tsunami earthquakes seem to be tied to subduction-zone segments adjacent to sediment starved or partly sediment filled trenches. Future work will further explore this possible correlation.

**Poster**

## Structure and active tectonics of the sediment starved North Chilean continental margin and the oceanic Nazca Plate

**Jacob Geersen[1], Jan H Behrmann[1], Ingo Klaucke[1], Heidrun Kopp[1], Dietrich Lange[1], César R Ranero[2], Udo Barckhausen[3], Christian Reichert[3], Anne M Tréhu[4], Eduardo Contreras-Reyes[5]**

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The erosive North Chilean margin represents an endmember margin in terms of trench sediment thickness and related sediment flux to the forearc. Due to a series of recent (1995 Antofagasta, 2007 Tocopilla, 2014 Iquique) and anticipated (Northern Chile seismic gap) earthquakes, the margin is in the focus of international attention with multiple ongoing projects. Here we use multibeam bathymetric data in combination with backscatter information, sub-bottom profiler data, and seismic reflection lines to investigate the tectonic regime and its along-strike heterogeneity. Along the entire middle and upper continental slope we find widespread extensional faulting with some of the faults outlining a 500 km long N-S trending ridge that may represent a paleo-cordillera. At the lower slope, the intensity of normal faulting varies along the margin. In a segment of the seismic gap (20.8°-22°S), normal faults extend close to the trench. Similar normal faults cutting the lower slope are neither observed further north (2014 Iquique earthquake area) nor further south (2007 Tocopilla earthquake area). A possible explanation for the lower slope normal faults could be repeated shallow earthquake rupture in the past. In addition to localized extensional deformation, the lower slope is shaped by slope-failures, conical re-entrant embayments, and NW-SE trending anticlines and synclines. The complex pattern of lower slope deformation results from the interplay of subducting lower-plate relief, gravitational forearc collapse, and the accumulation of permanent deformation over multiple earthquake cycles. Along the entire margin we find little evidence for fluid seepage. Considering the heavily faulted upper-plate, the lack of fluid seepage could be controlled by a lack of fluid sources in this poorly sedimented margin adjacent to the hyper-arid Atacama Desert. More detailed mapping and ground truthing campaigns are, however, needed to confirm the absence of fluid seepage. Morphologic changes along the forearc partly resemble structural variations of the oceanic Nazca Plate. The latter is primarily shaped by a spreading related abyssal hill fabric and bending related horst-and-grabens. Both, spreading fabric and horst-and-grabens are regionally overprinted by the NE-SW trending Iquique Ridge which collides with the forearc between around 20-21°S. South of the ridge-forearc intersection, bending-related horst-and-grabens are present whereas farther to the north new horst-and-grabens do not develop and bending is likely accommodated by reactivation of the paleo-spreading-centre faulting fabric.

**Talk**

## MOVE-ON: Models and Observations of Vertical Material Flow on the lithosphere with an open invitation to participate in the cooperative scientific meeting (Rundgespräch) to initialize the DFG Priority Programme Initiative “Move-On” (Fulda, 02.10.2018 – 05.10.2018)

**Ulrich A Glasmacher[2], Hans-Peter Bunge[1], Anke M Friedrich[1]**

*[1]Ludwig-Maximilians-Universität München, Germany; [2]Universität Heidelberg*

The aim of the scientific meeting of the research initiative “Move-On” is to discuss the *state-of-the art* of the **plume-driven vertical material flow in the non-lithospheric mantle, and its influence to the dynamic of the asthenosphere, the lithosphere,** and **the earth surface.** The outcome of the meeting combined with published knowledge will strengthen the “**unifying Plume-Mode-Stratigraphic Model (uPMSM;** Friedrich et al. 2018; Bunge and Glasmacher 2018**)”** and provide scientific key questions as basis for the proposed research concerning the evolution of the **Central European Lithosphere** from the Upper Cretaceous to the Miocene within the Priority Program “Move-On”-proposal to be submitted to DFG in November 2018. The **“uPMSM”** predicts that the vertical material flow in the non-lithospheric mantle leads to modifications to the lithosphere and its surface, including formation of a topographic dome, voluminous volcanic eruption, emplacement of dike swarms, and reorganization of the drainage pattern over broad regions. Changes of the topography include the evolution, reactivation, and horizontal migration of tectonic structures, rock and surface uplift, subsidence and inversion of sedimentary basins, and climate change. We are convinced that our community will advance this debate in major ways due to significant progress in geodynamical whole mantle convection models and their visualization, a long debate within DFG-funded research programs such as the SPP 1375 SAMPLE and other interdisciplinary efforts to bring experts from different fields together, the availability of high-precision geochronological and

biostratigraphic methods, and a recently formulated unifying **"uPMSM"** that provides the possibility to translate the technical outcome of mantle geodynamic models to the known geological record and to so far unconnected features of the sedimentological record (unconformities, hiatus, inversions) in a systematic and testable way.

Therefore, we suggest testing the **"uPMSM"** using field observations in a continental intraplate environment, where the predicted processes are accessible. The Central European Lithosphere with its Cretaceous to Miocene climate, sedimentary, tectonic, and magmatic activities (**Central European Cenozoic Igneous Province: CECIP)** provides continuous record in all necessary geological archives. The upper Cretaceous compressive event (Reicherter et al., 2000; Kley and Voigt 2008; see also Meschede 2012) restructured the European Lithosphere, reactivated faults, and possibly provided the pathways for the Miocene vertical material flow of the CECIP. The Upper Cretaceous compressional and the Miocene formation of the CECIP, and post-volcanic activities bracket the time frame that allows testing and verifying the **"uPMSM"**. Please contact one of us if you wish to participate in the initiative.

**Talk**

## New Developments in Understanding the Origin of South Atlantic Intraplate Volcanism (Tristan-Gough-Walvis, Discovery and Shona volcanic tracks)

**Kaj Hoernle[1,2], Folkmar Hauff[1], Stephan Homrighausen[1], Joana Rohde[1], Antje Dürkefälden[1], Reinhard Werner[1], Jörg Geldmacher[1], Maxim Portnyagin[1], Dieter Garbe-Schönberg[2], Paul van den Bogaard[1], Jo-Anne Wartho[1]**

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The mantle plume (hotspot) hypothesis is nearly as old as the theory of plate tectonics (Morgan 1971, Nature230). Hotspot tracks, formed when lithospheric plates move over a quasi-fixed mantle plume, derived from as deep as the core-mantle boundary, have played an important role in constraining plate motion and providing clues to the composition of Earth's mantle. The Tristan-Gough volcanic track, a classic hotspot track, extends from the Etendeka Flood basalts along the Walvis Ridge to the active islands of Tristan da Cunha and Gough. Within the last 10 years, there have been numerous important developments and new insights into the origin and evolution of this and other South Atlantic hotspots. Although long controversial (Baksi 2007a,b, SpecPapGeolSocAm430), an age progression along the Tristan-Gough-Walvis hotspot track (of 31 mm/a) has now been unequivocably established (Homrighausen et al. in revision, GCA). The age progression, together with seismic tomography (French and Romanowicz 2015, Nature525; Schlömer et al. 2017, EPSL462) and high $^{3}He/^{4}He$ in Etendeka picrites (Stroncik et al. 2017, Geology45), provides strong support for an origin of this hotspot track from the lower mantle through the plume head/tail model (Richards et al. 1989, Science246). New insights gained in recent years into the South Atlantic hotspots include: 1) Tristan-Gough hotspot track has been bilaterally geochemically zoned for the last ~70Ma along the Tristan and Gough subtracks in the Guyot Province (Rohde et al. 2013, Geology43) and the neighboring Discovery hotspot track to the south for the last 40Ma (Schwindrofska et al. 2016, EPSL441), being the first zoned hotspot tracks identified in the Atlantic and showing zonation over the longest time span of any hotspots; 2) Tristan-Gough hotspot track has a Gough-type enriched mantle one (EMI) end member composition during its earlier (~70-135Ma = Walvis Ridge and Etendeka/Parana flood basalt) history (Hoernle et al. 2015, NatComm6); 3) The main composition of the Northern Discovery and Shona hotspot tracks is also Gough-type EMI (Hoernle et al. 2016, Geology44; Schwindrofska et al. 2016); 4) Unexpected late-stage volcanism on the Walvis Ridge (20-40Ma younger than basement) and Shona hotspot track (~40Ma younger) have end member HIMU (high time-integrated $^{238}U/^{204}Pb$)-type composition, similar to St. Helena Island (Homrighausen et al. 2018a,b, EPSL492, ESR182); 5) Late-stage Walvis Ridge volcanism shows an age progression. The new results and their implications will be discussed in the talk, in particular the origin of the enigmatic late-stage volcanism.

**Poster**

## Melt processes of ultramafic mantle rocks of the Troodos Ophiolite: A case study of trace elements in clino- and orthopyroxene

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The Troodos Ophiolite is a remnant of 91 Ma Tethyan oceanic lithosphere obducted onto the Anatolian Plate. Although it is one of the best preserved and most studied worldwide, the tectonic setting of this supra-subduction zone ophiolite is still debated. Most previous geochemical studies of the Troodos Ophiolite have been carried out on the volcanic rocks. This work focuses on the mantle peridotites of Troodos, which yield complimentary valuable information about mantle heterogeneity and melting processes. For this study we measured peridotite mineral major element compositions and trace element concentrations of clino- and orthopyroxenes from both, the ultramafic section of the Troodos Ophiolite and fore-arc peridotites from the Tonga Trench. For comparison we used a global dataset of abyssal peridotites. Troodos peridotites range from slightly depleted lherzolite over harzburgite to dunite and pyroxenite. Chromium-numbers [Cr# = Cr/(Cr+Al)] of chrome-spinels (0.23 – 0.81) and chondrite-normalized MREE/HREE-ratios of clinopyroxene [e.g. $(Gd/Yb)_N$: 0.37 – 1.50] and orthopyroxene [e.g. $(Gd/Yb)_N$: 0.04 – 0.21] indicate melt extraction from 9 to 21 %. $Al_2O_3$ contents of orthopyroxene, which are highly sensitive to melt depletion, are negatively correlated with Cr#s of residual spinel. Troodos peridotites show $Al_2O_3$ contents from 0.84 to 4.43 wt%. These characteristics coincide with values from fore-arc and back-arc peridotites, whereas abyssal peridotites from slow to moderate spreading axes show generally lower Cr#s (0.11 – 0.35), higher $Al_2O_3$ contents (3.12 – 5.78 wt%) and higher chondrite-normalized MREE/HREE-ratios in clinopyroxene [$(Gd/Yb)_N$: > 0.88] and orthopyroxene [$(Gd/Yb)_N$: > 0.44]. Spoon-shaped REE patterns of clinopyroxene show enrichment of LREE, which probably indicate melt/rock interactions during ascent and/or subsequent magma percolation events. Elevated ratios of fluid-mobile trace elements relative to non-fluid-mobile elements of similar incompatibility (including Pb/Ce and Sr/Nd) compared to abyssal peridotites can possibly be explained by re-fertilization with hydrous fluids and/or sediment melts. These geochemical characteristics indicate an origin by complex melt depletion and re-enrichment events in a subduction-related environment. Mineral compositions of Troodos mantle rocks extend to more depleted values than many abyssal peridotites, consistent with a fore-arc or back-arc origin for the Troodos Ophiolite.

**Poster**

## Does intracontinental subduction occur in the Pamir? Inferences from the foreland fold-and-thrust belt in Kyrgyzstan and western China

**Jonas Kley[1], Edward R. Sobel[2], Johannes Rembe[2], Thomas Voigt[3], Chen Jie[4], Langtao Liu[5]**

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The Pamir mountains form the western extension of the Tibetan plateau, shifted about 300 km northwards relative to main Tibet. The northward convex Pamir arc is underlain by a steeply south-dipping Benioff zone, originally thought to reflect intracontinental subduction. A more recently proposed delamination model holds that Indian lithosphere has forcefully peeled off Asian lower crust and mantle to form the Pamir slab. Both models predict that about 300 km of convergence were accommodated in the Pamir, creating the northward salient and slab. The Main Pamir Thrust (MPT) and the north-verging, thin-skinned thrust belt of the External Pamir (EP) in its footwall represent the Cenozoic foreland fold-and-thrust belt. We describe the MPT/EP system and its variations from the Altyn Dara valley in the east (Kyrgyzstan) to the Yimaik valley in the east (western China) over an along-strike distance of some 270 km. The MPT everywhere emplaces rocks of Carboniferous age, including thick successions of pillow lavas, over younger strata. In the east, the MPT is located close to a large Mesozoic thrust sheet of greenschist to amphibolite-grade metamorphic rocks with possible affinities to the Karakul-Mazar arc domain of the Northern Pamir. The EP generally comprises a northward younging succession of Permian/Triassic through Neogene strata. In the west, these strata form a northward imbricated stack of thin, often refolded thrust sheets. In the east, the EP widens to occupy the entire width of the westernmost Tarim basin.

Semi-balanced cross-sections of the EP system suggest 75 to 30 km of shortening decreasing from west to east. Displacement on the MPT is not well constrained but very likely too small to match the postulated 300 km of convergence together with shortening in the EP. Restoration of the shortened cover also indicates that the low-angle MPT cuts into basement too far south to simply link up with the top of the steeply dipping Pamir slab imaged by geophysical methods. We propose that new evidence for a Mesozoic extensional (backarc?) basin allows for a pre-Cenozoic curved shape of the Pamir. The Cenozoic shortening required to obtain the present-day curvature could thus be substantially less than 300 km and might have been largely accommodated by the EP/MPT thrust belt. We speculate that rollback of a slab originally formed by subduction of continental lower crust and/or a remnant of the Mesozoic backarc may have moved the location of the slab northward and increased its length.

**Talk**

## Mesozoic-Cenozoic exhumation and uplift in Central Europe – part II: mechanisms and diagnostic criteria

**Jonas Kley[1], Fabian Jähne-Klingberg[2], Hilmar von Eynatten[1], István Dunkl[1]**

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The Mesozoic-Cenozoic intracontinental Central European basin system comprises many areas that were uplifted during some period of the basin history as documented by incomplete sedimentary successions, unconformities, present-day elevations of marine strata, recent erosion and topography. The uplifting areas vary strongly in size, uplift magnitude and duration, suggesting a variety of underlying mechanisms. Differences in wavelength, amplitude and persistence over time probably offer the best diagnostic criteria for pinpointing specific processes. Long-standing, several hundred Myr-scale highs such as the Bohemian Massif, the London-Brabant Massif and Ringkøbing-Fyn High have slightly thickened crust that apparently escaped to some degree the nearly pervasive destruction of Paleozoic orogenic crustal roots. A rather enigmatic feature is the large, long-lived crescent-shaped area of uplift surrounding the North Sea Basin in the west and south and including Great Britain and the German uplands. It first appears on Early Cretaceous paleogeographic maps and, after being partially flooded during Late Cretaceous sea-level highstand, was revived in latest Cretaceous and Cenozoic time. The absence of subsidence over some 100 Myr may indicate the isostatic effect of a slowly thinning lithospheric mantle. Increasing mantle temperature through the Late Cretaceous and Cenozoic in Central Europe is consistent with sparse occurrences of latest Cretaceous basalt and three Cenozoic rifts (Upper Rhine graben, Lower Rhine graben and Eger rift) arranged in a kind of triple junction geometry around a central area with more frequent and voluminous Miocene basalt eruptions. In addition, short-wavelength, high-amplitude uplifts were created by Late Cretaceous thrusting and basin inversion over a 20 Myr interval. It can be demonstrated now from thermochronologic data that the small-scale thrust-related uplifts were superimposed on regional uplift and denudation in the German uplands (see the first part of this contribution). This regional uplift occurs on the crescent-shaped North Sea borderland introduced above, but its rapidity suggests a process other than lithospheric thinning, possibly a pulse of mantle upwelling inducing dynamic topography. If this inference is correct, the total Late Cretaceous uplift signal was caused by three different mechanisms operating at different rates and spatial scales. Intraplate deformation can be viewed as largely elastic strain caused by interfering tangential and vertical loads that arise from plate motions and mantle convection. Extricating the individual contributions remains an observational and conceptual challenge.

**Poster**

## Zircon grains from serpentinite of the Voykar Massif, Polar Urals: Trace elements, U-Pb and Lu-Hf isotopic data

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The Voykar Massif consists of an ultramafic complex in the NW, followed by a mafic complex and an evolved island arc to the SE. Previous radiometric dating has yielded a late Neoproterozoic age (585±6 Ma; Savelieva et al. 2007) for the ultramafic complex, a range of late Cambrian to Silurian ages (428±7 to 490±7 Ma; Khain et al. 2008, Remizov et al. 2010, Estrada et al. 2012) for the mafic complex, and Early Devonian ages (c. 390–400 Ma; Estrada et al. 2012) for the evolved island arc. The mafic complex is dominated by gabbro, dolerite, and basalt with minor andesite and plagiogranite formed in a supra-subduction zone environment. By the river Lagortayu, the mafic complex also contains serpentinite fragments with zircon grains that are visible in thin section.

LA-ICP-MS U-Pb dating of the zircon grains yield an upper intercept age of 548±5 Ma with an age range of 527–549 Ma. Additionally, few older grains up to 3277 Ma were found. Trace element patterns of the zircon grains show fractionation from high HREE to low LREE with pronounced positive Ce and negative Eu anomalies. Discordant grains and those with with younger ages (<548 Ma) are enriched in LREE without Ce anomaly. Hafnium isotopic data of the main age group show 176Hf/177Hf(t) from 0.28242 to 028249 and εHf(t) ranging from +1.9 to -1.0. Two grains show lower 176Hf/177Hf(t) and εHf(t) (0.28228 and 0.28229; -5.6 and -6.5, respectively). The older grains mostly exceed the ratios for the depleted mantle. The previously obtained age for the ultramafic complex and our new age on mantle-derived serpentinite indicate zircon formation in the mantle during the Timanian Orogeny. Although a primitive island arc signature was found for the mafic complex, the evolved Hf isotope data point to an involvement of a crustal component in the underlying mantle to different extents, which is expressed by two Hf isotope groups.

References:

Estrada S et al. (2012): ZDGG 163/1: 9-42.
Khain, EV et al. (2008): Doklady Earth Sci. 419 A: 392-396.
Remizov DN et al. (2010): Doklady Earth Sci. 434: 1235-1239.
Savelieva GN et al. (2007): Geotectonics 41: 105-113.

**Poster**

## Do thermochronological data and stratigraphic records store plume movement?

**Florian C. Krob[1], Ulrich A. Glasmacher[1], Hans-Peter Bunge[2], Anke M. Friedrich[2], Peter C. Hackspacher[3]**

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Vertical movements have an important impact in various plate tectonic environments, connecting endogenic and exogenic dynamic forces (Bunge & Glasmacher, 2018). Therefore, the timing, rates, and causes of vertical movements are important for quantifying the dynamic of topographic evolution of large surface areas on long time scales. Whereas timing, rates, and causes of vertical movements in orogenic environments are reasonable understood, similar knowledge within the rift to passive margin environment, and within plate interiors is partly lacking.

Recently, Friedrich et al (2018) derived a stratigraphic framework that reveals surface effects of sedimentation and erosion (unconformities and hiatuses) predicted by the ascending mantle plume model of Campbell and Griffiths (1990). Regional-scale erosion dominates above the plume centre prior to plume arrival at the base of the lithosphere, followed by extensional collapse and flood-basalt eruption, while a nearly complete sedimentary record can be preserved in distal regions that did not experience plume-related surface uplift. Intermediate sedimentary sections are complex: they undergo surface uplift and erosion followed by subsidence and sedimentation, and renewed outward-directed uplift and erosion as the plume head collapses and spreads laterally.

In this work, published stratigraphic records of South America and South Africa were compared, and viewed in the frame of the rising plume model (Friedrich et al., 2017). Furthermore, an extensive thermochronological data set from Brazil (Krob et al., subm.) and Namibia (Menges et al., in prep) were tested against the revealed geological evolution during the rise of the Parana-Etendeka plume.

Campbell, I.H., Griffiths, R.W., 1990. Implications of mantle plume structure for the evolution of flood basalts. Earth and Planetary Science Letters 99, 79–93.

Friedrich, A.M., Bunge, H.-P., Rieger, S.M., Colli, L., Ghelichkhan, S., Nerlich, R., 2018. Stratigraphic framework for the plume mode of mantle convection and the analysis of interregional unconformities on geological maps. Gondwana Research http://dx.doi.org/10.1016/j.gr.2017.06.003.

Krob, F., Karl, M., Glasmacher, U.A., Perner, M., Hackspacher, P., Stockli, D.F. Long-term geological evolution of the Gondwana continental margin of South-Eastern Brazil. Submitted to Gondwana Research, 2018

Talk

## The stable tungsten isotope composition of modern igneous reservoirs

**Florian Kurzweil[1], Carsten Münker[1], Ronny Schoenberg[2]**

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Tungsten is fluid mobile in the Earth's crust and mantle, but its geochemical cycle in different plate tectonic environments still remains poorly understood. Tungsten stable isotopes represent a novel tool with the potential to better constrain this cycle, because of possible W isotope fractionation during changes in redox-state (valence states +4 and +6) and coordination (tetrahedral and octahedral). Our analytical protocol, using a $^{180}$W-$^{183}$W double spike, yields an external reproducibility of ±0.018‰ (2 s.d.) in $\delta^{186/184}$W and allows to resolve small stable W isotope variations between different igneous reservoirs [1].

We present stable W isotope data for lavas from mid-ocean ridge basalts (MORBs), ocean island basalts (OIBs) and various subduction-related settings (Cyprus; Papua New Guinea; Solomon; Sunda). The $\delta^{186/184}$W values of MORBs (+0.088 ± 0.017 ‰, n = 8) and OIBs (+0.078 ± 0.020 ‰, n = 5) show a narrow range and are analytically indistinguishable. However, subduction related lavas from the ophiolite complex in Cyprus show significantly higher $\delta^{186/184}$W values up to +0.195 ‰. These rocks also show elevated W/Th, which indicates selective W enrichment from sediment derived fluids with heavy W isotope composition. In contrast, lavas from the Sunda arc show low $\delta^{186/184}$W values down to -0.009 ‰. High W and Th concentrations but overall low W/Th ratios in these rocks suggest the addition of a sediment melt component, which is isotopically light with respect to W. Thus, major stable W isotope anomalies seem to be related to low-temperature processes during sedimentation and diagenesis. When only considering rocks with canonical W/Th, we observe only small variations in $\delta^{186/184}$W values. However, a slight positive co-variation of $\delta^{186/184}$W with $SiO_2$ in these rocks might indicate some stable W isotope fractionation during fractional crystallisation. Other parameters like $f(O_2)$ or residual rutile seem to have little effects on $\delta^{186/184}$W values.

In summary, our results demonstrate that fractional crystallisation and, particularly, addition of subducted sediment components appear to affect stable W isotope compositions of igneous reservoirs. Thus, stable W isotope measurements represent a promising geochemical tool to better constrain the cycle of W in modern and ancient igneous reservoirs.

[1] Kurzweil *et al.* (2018) *Chem. Geol.* **476**, 407-417.

Poster

## CORRELATIONS OF OCEANIC SPREADING RATES AND HIATUS SURFACE AREA IN THE NORTH ATLANTIC REALM

**Yulia Vibe[1,2], Anke M Friedrich[1], Hans-Peter Bunge[1], S. R. Clark[2]**

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The North Atlantic realm is strongly affected by the Iceland–Jan Mayen mantle-hotspot system. Its strength varied over time with consequences for evolving plate driving forces and topography maintained dynamically by convective stresses in the mantle. Here, we combine reconstructions of Atlantic spreading rates with maps of geological hiatuses at the scale of continental Europe. We extracted hiatus information from the 1 : 5–Million–Scale International Geological Map of Europe and Adjacent Regions (Asch, 2003, 2005) — at the available temporal resolution of geological series — to construct hiatus maps for the basal Paleocene to Pliocene series boundaries. The maps allow one to visualize first-order changes in hiatus intensity and spatial extent, serve as a reference frame and proxy-tool for paleogeographic analysis of topography, and reveal that episodes of spreading acceleration in the North Atlantic coincide with episodes of erosion/non-deposition intensification at the continental scale of Europe. Such patterns are not predicted by the plate mode of mantle convection, but are generally consistent with the plume mode. Interregional-scale hiatus mapping may serve as a powerful new technique to visualize these effects, especially once the temporal resolution of the maps will have been refined. Interpretation of such hiatal surfaces is most effective in context with theoretical frameworks, such as the plume-mode of mantle convection.

Talk

## Mesozoic-Cenozoic exhumation and uplift in Central Europe – part I: spatial extent, pattern, magnitude and timing

**Hilmar von Eynatten, István Dunkl, Veit-Enno Hoffmann, Annemarie Simon, Jonas Kley**

*Georg-August-Universität Göttingen, Germany*

Following the Variscan orogeny large parts of Central Europe were covered by extensive sedimentary successions deposited in a complex intracontinental basin system. The subsindence history was repeatedly punctuated by breaks and uplift events of varying magnitude, location and spatial extent. Among these, Cretaceous exhumation and uplift has reached by far the highest magnitudes and effected individual blocks within a huge area extending, at least, from the Ardennes in Belgium to the Holy Cross Mountains in south-central Poland. Beyond these uplifted blocks, inverted sedimentary (sub)basins are common in the Central European Basin system, which includes significant parts of The Netherlands, the southern North Sea, Denmark, northern Germany, and Poland. The uplifted blocks include (i) prominent fault-bounded mountainous regions like the Harz Mountains or the Karkonosze Mountains, which experienced pronounced Late Cretaceous exhumation, and (ii) other basement blocks, which experienced less pronounced and longer-lasting Mesozoic-Cenozoic exhumation like the Rhenish Massif or the Holy Cross Mountains. The tectonic and/or other causes for distribution, magnitude and timing of uplifted areas in Central Europe represent a long-lasting matter of debate, including models of strike-slip faulting and intraplate contraction and thrusting related to either Alpine orogeny or Africa-Iberia-Europe convergence. However, there is still no consistent geophysical-geological model explaining the Mesozoic to Cenozoic formation of topography in Central Europe, which essentially persists to the present day.

In this contribution we will (i) review the existing literature on thermochronology and exhumation of the uplifted basement blocks in Central Europe, and (ii) present new apatite fission track and apatite and zircon (U-Th)/He data from areas between these blocks, focusing on central Germany. The results indicate that the area experiencing Mesozoic subsidence followed by pronounced Late Cretaceous exhumation and uplift must have been considerably larger than previously thought and is thus not restricted to thrust-related basement blocks. This implies that the causes for basement thrusting might be decoupled from the causes for the roughly contemporaneous uplift of the entire area, i.e. basement thrusting and (sub)basin inversion was superimposed on regional uplift of much larger wavelength. Possible mechanisms to explain the complex pattern of subsidence, exhumation and uplift will be discussed in the second part of the contribution.

# 2d) Tectonic systems

Poster

## Paleomagnetism and tectonics from the late Pliocene to late Pleistocene in the Xalapa monogenetic volcanic field, Veracruz, Mexico

**Amar Agarwal[1], Luis Manuel Alva Valdivia[2], Bernardo García-Amador[2]**

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The Xalapa monogenetic volcanic field, Veracruz, Mexico is located at the eastern end of the Trans-MexicanVolcanic Belt[1]. This study uses specimens from, 0.8 kato 5.96 ± 0.156 Ma, Xalapa lava deposits and from, 4.5 ± 0.028 Ma, La Concha ignimbrite[2]. The study identifies the magnetic mineralogy by reflected light microscopy, thermomagnetic curves, andcoercivity estimates. It further defines the magnetic domain size distribution by hysteresis plots, Day diagrams,and First Order Reversal Curves. The Xalapa basalts present, 5 to 50 µm large, low-Ti titanomagnetite cubic and skeletal grain that sporadically have fine trellis type ilmenite lamellae. The magnetic domain type represents a mixture of single and multi-domain without superparamagneticparticles. Comparison of the calculated polarity and the radiometric dates with the GPTS allowed improvement of the age of five lava flows. Characteristic remanent directions and virtual geomagnetic poles are also calculated. The characteristic remanent directions are used to establish the magnetostratigraphy and to identify the net rotation experienced, at each site, since the emplacement. The results allow the identification of the rotation domains, and R´, P and Y-shears, active since past ~2.5 Ma in the region. The Río Actopan fault has both normal and sinistral components, in contrast to the earlier schools of thought supporting just one component and disregarding the other [2,3].

References

1. Alva-Valdivia, L. M. *et al.*Paleomagnetic and AMS studies of the El Castillo ignimbrite, central-east Mexico: Source and rock magnetic nature. *J. Volcanol. Geotherm. Res.***336,**140–154 (2017).

2. Rodríguez, S. R., Morales-Barrera, W., Layer, P. & González-Mercado, E. A quaternary monogenetic volcanic field in the Xalapa region, eastern Trans-Mexican volcanic belt: Geology, distribution and morphology of the volcanic vents. *J. Volcanol. Geotherm. Res.***197,**149–166 (2010).

3. Andreani, L. *et al.*The Neogene Veracruz fault: evidences for left-lateral slip along the southern Mexico block. *Bull. la Société géologique Fr.***179,**195–208 (2008).

Talk

## The tectono-sedimentary evolution of the Promina Beds caused by contrasting styles of deformation along-strike the External Dinarides

**Philipp Balling[1], Bruno Tomljenović[2], Kamil Ustaszewski[1]**

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The deformation of the Dinarides fold and thrust belt on the Balkan Peninsula records the convergence between the European and the Adriatic plates. The Internal Dinarides consist of ophiolite-bearing nappes deformed during Cretaceous times. The External Dinarides consist of mainly shallow marine Mesozoic and Cenozoic carbonate platform deposits, which were folded and thrusted in the Eocene. In the most external part, deformation is dated by the deposition of a heterogenous 2 km thick mid-Eocene to late Oligocene syn-tectonic sedimentary sequence – the Promina beds. The Promina beds extend along-strike for about 200 km and unconformably overlie folded platform carbonates. The Promina Basin shows an overall trend from deeper over shallow marine to fluvial depositional conditions, documenting the evolution from an underfilled to an overfilled basin, in which subsidence could not keep up with sediment supply. Although the sedimentary record of the Promina Beds is well studied, the tectonic framework is unclear. It is a matter of debate whether the accommodation space was created by a piggyback or in a subsiding flexural foreland basin.

To validate the tectonic framework of the Promina Basin, we kinematically forward- and backward-modelled three balanced cross-sections on both sides of a large-scale dextral strike-slip fault. This fault aligns with a lateral pinch-out of Permian evaporites in the subsurface. Due to the presence vs. absence of the evaporites, the style of deformation in the thrust belt portions on either sides of the fault is contrasting. The deformation in the western segment is related to a SW-vergent duplex and a shallower NE-vergent back-thrust. By contrast, the eastern segment of the fault is characterized by a SW-vergent nappe stack, which tectonically doubles the entire Adriatic Carbonate Platform.

Our results of the kinematic evolution of the complexly deformed hinterland suggests that the most plausible setting for the subsidence of the Promina Basin was a Paleogene flexural foreland basin. The basin subsided due to lithosphere flexure induced by tectonic doubling of the Adriatic Carbonate platform rocks. Since late Oligocene times the basin was overfilled and could not accommodate any more sediments. Most of the present-day outcropping Promina sediments are located solely in close proximity to the eastern nappe stack. The fact that the Promina Beds contain only reworked material of the External but no fragments of the Internal Dinarides proves that the nappe stacking created a paleo drainage, which only affected the upper nappe stack equal to the present-day drainage network.

**Poster**

## Morphotectonic analysis of basement and cover units in eastern Bavaria, SE Germany - insights into the deeper crustal architecture?

**Andreas Eberts, Anna Schaarschmidt, Wolfgang Bauer, Harald Stollhofen, Helga de Wall**

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The topographic expression of landscapes directly depends on the interaction between exposed rock type, erosion and tectonic deformation. In areas where high rates of active deformation prevail, the effects of faulting and folding are often immediately transferred to the Earth's surface. By contrast, in areas where ongoing, rapid deformation is absent, as it is assumed for large parts of eastern Bavaria, erosional processes need to utilize gradients in erodibility to uncover already existent tectonic structures. In that case, resulting topographic features are not visible as well-defined fault scarps but as linear to curvilinear river valleys, ridgelines or slope breaks. Because these lineaments outline structures that formed during ancient tectonic events, mapping of them yields important information about the general structural framework of the subsurface.

Here, we present results from an integrated study, using high-resolution digital elevation models from airborne LiDAR surveys combined with gravity data to reveal the morphotectonic feature inventory of eastern Bavaria, SE Germany, and its relation to the underlying crustal architecture. The studied area comprises the western border zone of the Bohemian Massif, a region well known for hosting some of the largest fault zones existing in Central Europe, such as the Pfahl Fault Zone (PFZ) and Danube Fault Zone (DFZ). Post-Variscan to Alpine reactivation of earlier structures led to a complex structural pattern along these faults and ultimately resulted in the uplifted and exposed basement complex of the Bohemian Massif.

Our results show that the investigated area is segmented into several domains of different orders. 1$^{st}$ order domains, best delineated in gravity data, are thought to represent large crustal blocks which partly root into the upper mantle. These are assigned to the Saxothuringian, Teplá-Barrandian and Moldanubian crustal units. In contrast, 2$^{nd}$ order domains additionally show distinct variations in the arrangement of topographic lineaments and in other DEM-specific parameters such as surface roughness indices and altitude distributions. In the Bavarian Forest, for example, a central domain of high gravity is also characterized by predominantly N-S oriented lineaments and an increased surface roughness. Furthermore, 2$^{nd}$ order domains are separated by large topographic lineaments, some of which situated in close vicinity to already known fault zones such as the PFZ and DFZ. However, our study also identifies previously unknown locations of ancient fault zones, ultimately indicating an even more complex structural evolution and crustal architecture of eastern Bavaria and the western border zone of the Bohemian Massif.

**Talk**

## Regional velocity field variations in the Southern Andes are kinematically related to the Liquiñe-Ofqui Fault Zone: evidence from scaled analogue experiments

**Jan Oliver Eisermann, Ulrich Riller**

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With a length of about 1000 km, the Liquiñe-Ofqui Fault Zone (LOFZ) in the Southern Andean Volcanic Zone (SAVZ) ranks among the largest intra-arc fault zones on Earth. The fault zone is generally believed to have formed in a dextral transpressive setting attributed to oblique subduction of the Nazca Plate below the South American Plate. West of the LOFZ, GPS vectors indicate uniformly NE-directed velocities on the order of several centimetres per year, whereas east of the LOFZ velocities diminish abruptly to a few millimetres per year. Moreover, GPS vectors change from NE-directed to SE-directed vectors at the northern terminus of the LOFZ. Thus, the GPS velocity pattern in the SAVZ seems to be kinematically related to the LOFZ. Specifically, West of the LOFZ velocities are co-linear with the obliquity in plate convergence and, thus, indicate an absence of deformation partitioning. By contrast, the abrupt West-East GPS velocity gradient at the LOFZ points not only to a large component of dextral displacement but a considerable amount of shortening on the LOFZ. Moreover, the GPS velocity pattern may be caused by a northward propagation of the LOFZ tip.

In order to test, to what extent the GPS velocity pattern is kinematically related to the LOFZ, we conducted a series of crustal-scale analogue experiments using our MultiBox, which was designed specifically to simulate transpression. The box consists of two halves, each of which contains a piston, whereby one halve is mobile and moves relative to the fixed one parallel to the box midline, thereby inducing a velocity discontinuity. Our experiments are scaled to ordinary thicknesses of undeformed lower and upper crust. Experiments consist of a 2 cm thick silicone layer simulating the ductile lower crust, and a 2 cm thick layer of quartz sand with Mohr-Coulomb rheology for the brittle upper crust. Two cameras record the surface evolution during the experiments. Using 3D digital image correlation, surface deformation, topography and evolving faults of the experimental surface can be quantified.

We observed a change in orientation and magnitude of velocity vectors in our experiments, akin to the GPS velocity pattern at the northern LOFZ. Overall, deformation in our models is accomplished by oblique reverse faults. Deformation partitioning does not occur in our models. Our observations indicate that pure strike-slip faults, as a result of deformation partitioning, in a transpressive setting are not capable of causing the observed GPS vector field.

Talk

## Lu-Hf geochronology of eclogites from Norrbotten (Seve Nappe Complex, Scandinavian Caledonides)

**Kathrin Fassmer[1], Nikolaus Froitzheim[1], Raúl O.C. Fonseca[2], Carsten Münker[2]**

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The Seve Nappe Complex in the Scandinavian Caledonides represents the distal part of the margin of Baltica, which was subducted to depth of ultra-high pressure (UHP) metamorphism during the Caledonian Orogeny. In contrast to the (U)HP ages determined for the Western Gneiss Complex in Western Norway (ca. 400 Ma), which is interpreted to represent the subducted Baltican basement, the ages in the Seve Nappe Complex and related nappes are overall older (ca. 500 - 430 Ma). Given this reported age discrepancy, it is desirable to obtain a high-precision data-set based on one geochronological method. Therefore we have dated samples from different localities within the Seve Nappe Complex using Lu-Hf geochronology on garnet.

Lu-Hf ages have already been obtained for an eclogite from Tjeliken in northern Jämtland. The age of 458.1 ± 1.0 Ma for the eclogite is identical with the U-Pb zircon age of 458.9 ± 2.5 Ma for the surrounding gneiss (Fassmer et al. 2017).

In this study we report new Lu-Hf whole-rock- garnet ages of two eclogites from Norrbotten, which is situated ca. 200 km north of Tjeliken. The peak metamorphism there was dated with U-Pb and Sm-Nd on eclogites before and yielded ages that range between 475 and 504 Ma (Mørk et al. 1988, Essex et al. 1997, Root & Corfu 2012). We dated two samples from two different eclogite bearing units in Norbotten, one from the Northern (Tsäkokk) Lens and one from the Southern (Vaimok) Lens. Garnet in the eclogites shows a prograde major-element zoning and is Lu-rich in the core, indicating that these ages are related to garnet growth during pressure increase, i.e. subduction. The sample from the Tsäkokk Lens yielded ca. 489 Ma and the sample from Vaimok ca. 480 Ma. The two ages differ from each other outside analytical error.

The ages from northern Jämtland and Norrbotten imply that the whole Seve Nappe Complex has been subducted earlier than the Western Gneiss Region, possibly reflecting an arc-continent collision preceding continent-continent collision. Within the Seve Nappe Complex subduction ages seem to decrease from north to south.

Essex et al. 1997. Journal of Metamorphic Geology 15, 665–676.

Fassmer et al. 2017. Contributions to Mineralogy and Petrology, 172:103.

Mørk et al. 1988. Contributions to Minereralogy and Petrology 99, 344–351.

Root & Corfu 2012. Contributions to Mineralogy and Petrology, 163, 769-788.

Poster

## Importance of convergence angles on the evolution of fault patterns in transpression zones inferred from analogue modeling

**Rosa Johanna Flesch, Jan Oliver Eisermann, Ulrich Riller**

*Universität Hamburg, Germany*

Oblique plate convergence is ubiquitous on Earth and results in transpression at or near convergent plate boundaries. Transpression is defined as simultaneous horizontal simple shear and transverse shortening that leads to vertical extrusion of material in a defined deformation zone. Transpression generates complex fault patterns in the upper crust. In order to quantitatively assess the variability of patterns resulting from transpression, a series of scaled analogue experiments was performed using our MultiBox. In particular, we aimed at characterizing fault patterns arising from variable ratios of shearing and shortening velocities, while the initial thickness of analogue materials is kept constant.

The MultiBox consists of two halves, each of which contains a piston, whereby one halve is mobile and moves relative to the fixed one parallel to the box midline, thereby inducing a velocity discontinuity. Our experiments are conducted using viscous and brittle analogue materials that are scaled to thicknesses of undeformed lower and upper crust. Simple two-layer experiments consist of a 2 cm thick silicone (PDMS) layer simulating the ductile lower crust, and a 2 cm thick layer of quartz sand with Mohr-Coulomb rheology for the brittle upper crust. Two cameras record the surface deformation during the experiments. Using 3D digital image correlation, surface deformation, topography and evolving faults of the experimental surface can be quantified.

The velocity ratio between shearing and shortening in our series of analogue experiments is systematically altered to generate different convergence angles, resulting in different fault patterns. We find that the convergence angle influences profoundly the fault patterns. Notably, strike-slip fault patterns develop preferably at low convergence angles, whereas large convergence angles generate chiefly thrust fault-dominated patterns. Moreover, in most experiments thrust faults and lateral thrusts localize only after 1 h. Within the first hour, model fault activity is widely distributed, but is not visible to the human eye. However, the sub-millimeter resolution of our camera system is capable of visualizing and quantifying distributed deformation and how it relates to the localization of deformation. Our analogue modelling results promise to furnish important information on the influence of convergence angles on the evolution of upper-crustal fault patterns in transpressive deformation systems.

**Talk**

## A revised kinematic model for the Liquiñe-Ofqui Fault Zone, Southern Andes, based on recent compilation of thermo-chronological data and DEM analysis

**Paul Leon Göllner, Jan Oliver Eisermann, Ulrich Riller**

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The Liquiñe-Ofqui Fault Zone (LOFZ) is the most prominent fault zone of the Southern Andes. The LOFZ cuts the Patagonian Batholith and the modern Andean volcanic arc along-strike for more than 1000 km and is generally attributed to oblique subduction of the Nazca Plate underneath the South American Plate. Northward displacement of the Chiloé Block, a detached forearc sliver, points to an overall dextral displacement on the LOFZ. Therefore, the LOFZ is commonly regarded as a vertically dipping, narrow fault zone composed of two NNE-trending lineaments connected through a number of stepover faults. A compilation of published kinematic and thermochronological data as well as analysis of lineaments suggests a more complex architecture and deformation kinematics of the LOFZ.

Fission-track data along the LOFZ between 42° and 46° S point to enhanced reverse slip on the LOFZ in Miocene to Pliocene times. Between 38° S and 42° S, prominent lineaments demarcating the southern LOFZ segment transition into faults with variable strike and senses of displacement. Analysis of ASTER GDEM 2 high-resolution shaded relief digital elevation models reveal NE-trending lineaments between 42° S and 47° S. Along the entire fault zone, interconnected lineaments allow us to define individual fault-bound blocks along the LOFZ. Interpolated apatite fission-track ages indicate specific uplift rates for each block. Moreover, the northward increase in obliquity of lineaments with regard to major margin-parallel fault escarpments points to an along-strike change in tectonic style. Specifically, margin-parallel lineaments south of 42° S agree with margin-parallel northward displacement of the Chiloé Block. By contrast, NW-trending faults between 38° S and 42° S may result from the collision of the forearc sliver with rigid crust of the Central Andes.

In contrast to the preexisting, rather crude structural and kinematic view of the LOFZ, our reassessment of thermochronological and surface structural data requires reconsideration of intra-arc deformation kinematics of the overall dextral transpressive LOFZ. Most importantly, deformation appears to be distributed over a wide zone and forearc slivers are laterally displaced toward rigid crust of the Central Andes. Additionally, variations in uplift rates of individual fault-bound blocks call for a significant vertical displacements during the late Cenozoic. Collectively, these structural and kinematic characteristics agree well with current GPS vectors, which do not support elastic strain partitioning.

**Poster**

## Massivley dilatant faulting at divergent plate boundaries – a new model for faults in the upper crust at rift zones based on analogue models and field studies in Iceland

**Michael Kettermann[1], Christoph von Hagke[2], Lisa Winhausen[3], Daniel Bücken[4], Christopher Weismüller[5], Janos L. Urai[1]**

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Mid-oceanic ridges and rift zones at divergent plate boundaries show large amounts of extension and associated normal faulting. In volcanic rocks in areas like Iceland or the East African Rift these faults form as massively dilatant faults with surface apertures of up to tens of meters. While these surface structures have been studied in the past, there are many open questions caused by a lack of insights into the formation of dilatant faults. Structural predictions at depth are based on theoretical considerations using the failure of intact basaltic rocks as limiting factor for dilatantcy. However, it is widely accepted that subvertical cooling joints strongly affect the fault geometry both laterally and vertically, implying that a fault model based on intact rock is flawed. While opening mode failure at the surface can be observed and shear mode failure at large depths is assumed, the transition depths of the failure modes and resulting fault structures are not known.

We provide a new structural model of massively dilatant faults at rift zones down to several kilometers depth, building on a variety of analogue models and field data from Iceland. We can accurately model the near surface structures using a mechanically anisotropic (orthotropic) material and show that observed open fractures are often not representing the actual fault localization but merely the footwall-fracture of a tilted block covering the fault. Apertures of fractures measured in the field overestimate the true opening of the fault due to the tilting. Large unrecognized open fractures exist under tilted blocks.

Models using cohesive powder provide insights into the failure mode transition at depth. We can show that dilatancy exists much deeper than the theoretical considerations based on material strength suggest. The transition from opening to shear mode failure occurs as slightly curved fault plane, steeper near the surface and shallower at depth. Within this zone, patches of dilatant and shear mode failure alternate. Asperities in the fault can locally accumulate high stresses and fail in shear at shallow depths, while dilational jogs provide low differential stresses and dilatancy at depths larger than the strength of the material suggests.

Talk

## Pre-Variscan U-Pb zircon ages of the Texel Complex and the Schneeberg Complex (Austroalpine, Italy)

**Linus Klug, Nikolaus Froitzheim, Frank Tomaschek, Markus Lagos**

*Universität Bonn, Germany*

Despite intense Alpine overprint the Austroalpine Texel Complex and Schneeberg Complex at the western end of the Eoalpine High Pressure Belt inherit a Precambrian and Paleozoic record. With a geochronological approach the pre-Variscan situation of these units can be constrained. Laser ablation-ICP-MS U-Pb-dating on zircon yields ages for magmatic growth and metamorphism, as well as age spectra in sediments and for inherited zircon cores.

Two orthogneisses have been dated from the Saltauser Tal north of Meran (Italy). An amphibole-bearing orthogneiss from the Texel Complex yields a protolith age of 470±11 Ma. A leucocratic orthogneiss from the adjacent Marlengo Slice yields 449+7/-8 Ma as protolith age. The amphibole-bearing orthogneiss has a geochemical signature of an I-type volcanic-arc-granitoid, while the leucocratic orthogneiss shows S-type continent-collision- granitoid signatures. This is a typical situation for the Austroalpin basement, with an Ordovician acid magmatism at the northern margin of Gondwana evolving from a continental arc to a collisional setting (Schulz et al. 2008).

Detrital zircons from the Schneeberg Complex have been analysed from a quarzite and a garnet-bearing micaschist. Both samples yield youngest zircon populations of ca. 430 to 480 Ma, represented by zircons with magmatic zonation. The complete age spectra resemble the East African-Arabian Zircon Province (Stephan et al. 2018). This indicates a sedimentation age not older than 430 Ma.

The analysed zircons of orthogneisses and metasediments exhibit complex zoning including common inherited cores with magmatic, metamorphic or resorption textures and always late, narrow metamorphic rims. If these rims are of Variscan, Alpine or other origin is still under investigation.

The pre-Variscan situation of the Texel Complex is a continental basement intruded by Ordovician magmatism at the northern margin of Gondwana, while the Schneeberg Complex represents its sedimentary cover including eroded remnants of Ordovician to Silurian granitoids.

### References

Schulz, B., Steenken, A., Siegesmund, S. (2008). Geodynamics of an Alpine terrane – the Austroalpine basement to the south of the Tauern Window as a part of the Adriatic Plate (eastern Alps). - In: Siegesmund. S. Fügenschuh, B. Froitzheim, N. (eds.): Tectonic aspects of the Alpine-Dinaride-Carpathian system. Geol. Soc. London Spec. Publ., 298: 5-44.

Stephan, T., Kroner, U., Romer, R. L. (2018). The pre-orogenic detrical zircon record of the Peri-Gondwana crust. Geological Magazine, published online, 1-27.

Talk

## Styles of Late Cretaceous intraplate shortening in Central Germany - first results from the Altmark region, Saxony Anhalt

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The Late Cretaceous “hercynian” intraplate contraction affected large areas of Central Europe and created a variety of structures of different style. Many of these are due to inversion of basins and (half-)grabens, which originated in several events of distributed extension during Late Triassic and Late Jurassic/Early Cretaceous times, but they coexist with large basement-cored uplifts and detached thrust systems resembling structures typically known from fold-thrust-belts in the foreland of orogens.

In our contribution we present various fault zones in the Mesozoic cover of the Altmark area, a comparatively small (~8000 km$^2$) region that serves as an excellent case study area resembling the above mentioned structural spectrum of intraplate contraction. The results are based on a large-scale 3D modelling campaign carried out by the Geological Surveys of northern Germany. In the Altmark area we consulted approximately 6.500 km of interpreted 2D reflection seismic sections and ~700 deep boreholes to construct the existing fault network in 3D. Single fault strands in seismic sections were correlated to complex fault zones. Fault zone kinematics were derived from thickness distributions of selected stratigraphic units derived from regional depth maps.

Our results show that the Altmark area can be subdivided in areas of different tectonic style: (1) thick-skinned basement uplifts in the south, (2) an approximately 20 km wide dominantly thin-skinned fold-thrust-belt in the northern foreland and (3) a large area of basin and graben inversion in the northeast and northwest. This subdivision in combination with our “catalogue of fault zones” will help to better understand the structural configuration and the kinematics of intraplate contraction in Central Germany.

Poster

## Lu-Hf garnet geochronology of UHP-rocks: Investigations of the Tromsø Nappe (Northern Norway)

**Ina Martinet[1], Kathrin Fassmer[2], Irena Miladinova[2], Nikolaus Froitzheim[2], Peter Sprung[1,3], Raúl O.C. Fonseca[1], Carsten Münker[1]**

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The Tromsø Nappe represents the upper part of the Uppermost Allochthon of the Scandinavian Caledonides. The nappe is composed of metamorphic rocks such as eclogites, amphibolites, schists, marbles, and gneisses. Thermobarometric modelling for two eclogite-bearing units at Tønsvika and Tromsdalstind yielded P-T conditions of 3.36 GPa at 735°C for Tønsvika [1] and up to 3.2-3.5 GPa at 720-800°C for Tromsdalstind [2]. The samples thus reached UHP conditions, and in Tønsvika even metamorphic diamond has been found [3]. The host rocks of these eclogites were dated with various methods and gave age data scattering between 410 and 600 Ma (e.g. [4, 5]). The high-pressure event has been dated to 452.1 ± 1.7 Ma using U-Pb zircon dating [6].

Here, we present petrological and geochronological data for eclogite samples from Tønsvika and Tromsdalstind. The mineral assemblage of both samples comprises garnet, omphacite, retrograde plagioclase, amphibole, and rutile. Our data are the first Lu-Hf garnet ages for eclogites from this area. A five-point isochron for the Tønsvika eclogite yields an age of ca. 450 Ma. The eclogite sample of Tromsdalstind yields an age of ca. 445 Ma. The ages overlap within the uncertainty. Element distributions in garnet differ between both eclogite samples. We interpret zoned Mn distributions in garnet from the Tromsdalstind eclogite as preserved growth zoning. By implication, the Lu-Hf age thus dates prograde metamorphism. In contrast, Lu and Mn distribution in garnet from Tønsvika eclogite imply that Lu-Hf dates the cooling of the eclogite body. Our ages overlap the U-Pb age of Corfu et al. (2003), and we can therefore constrain UHP metamorphism to be a pre Scandian-event. We interpret the overlap of both ages as reflecting a fast subduction and exhumation cycle with a duration of only a few million years.

[1] Krogh Ravna & Roux (2006), *Int Geol Rev* **48**, 861-881.

[2] Janák et al. (2012), *J Metamorph Geol* **30**, 377-396.

[3] Janák et al. (2013), *J Metamorph Geol* **31**, 691-703.

[4] Griffin & Brueckner (1985), *Chem Geol* **52**, 249-271.

[5] Krogh et al. (1990), *J Metamorph Geol* **8**, 289-309.

[6] Corfu et al. (2003), *Contrib Mineral Petr* **145**, 502-513.

Poster

## MudRisk – a new tool for the detection of fluid pathways around mud volcanoes in Azerbaijan

**Lena Merz[1], Ayten Huseynova[2], Vugar Babayev[3], Elbay Babayev[2], Christoph Hilgers[1]**

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Mud volcanoes are abundant geological phenomena in the southern Caspian Basin related to very high subsidence and sedimentation rates. In Azerbaijan more than 200 mud volcanoes were mapped onshore. In the surrounding of the mud volcanoes ascending hydrocarbon rich fluids and gases affect groundwater and soil quality. Hydrocarbon systems are closely related to mud volcano fluid systems and fluids mainly consist of methane. The aim of our project is to map micro-seepage and draw conclusions about migration pathways of gas in the wider area of mud volcanism, as well as to evaluate the environmental influence of these seepages. Therefore, we couple Structure from Motion with methane measurements and soil and groundwater analysis and integrate all the data in a subsurface model.

We couple a hexacopter with a methane gas sniffer based on laser detection and map the area around mud volcanoes, where micro-seepage occurs along fractures often related to regional anticline systems. In a first field campaign we test this innovative method on selected mud volcanoes from different regions in Azerbaijan. Simultaneously we conduct photogrammetry of the area around mud volcanoes to image fracture systems and support the results from methane measurements. In addition to mapping fractures and related microseepage of methane by aerial photogrammetry on the ground around mud volcanoes, we study outcrops in order to understand the petrophysical characteristics of the lithologies related to fluid migration.

First tests of our new workflow were promising. Calibration measurements show concentrations of down to 10ppm x m for background noise of methane in the air and measurement limit of the laser detector. Errors can occur due to low or high reflection intensity of the laser beam, e.g. caused by sunlight or strongly reflecting surfaces. Other factors influencing the measurement are mostly caused by wind and air pressure conditions, which are continuously recorded during measurement. Data evaluation of a first field work campaign in different test areas in Azerbaijan will show us how to improve the workflow for future measurements.

Talk

## Lu-Hf geochronology and petrology of eclogites from the Eastern Alps: New constraints for the kinematics of the Eoalpine subduction zone

**Irena Miladinova[1], Niko Froitzeim[1], Thorsten J. Nagel[2], Marian Janák[3], Raúl O.C. Fonseca[4], Carsten Münker[4]**

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Eclogite-facies and partly ultrahigh-pressure metamorphic rocks are exposed in the Austroalpine high-pressure belt of the Eastern Alps. The east-west trending zone extends from Sieggraben to the east over Pohorje, Koralpe and Saualpe in the southeast towards the Texel complex in the west. The grade of the high-pressure metamorphism within the zone increases towards southeast, with maximum pressures and temperatures reaching up to 3.5-4.0 GPa and 850-900 °C in the Pohorje Mountains (Janák et al. 2015).

A detailed Lu-Hf isotopic study was performed on eclogites from different localities in the Eastern Alps - i.e. Koralpe, Saualpe, Sieggraben and Texel complex. Isochrons were calculated for every sample based on whole rocks as well as garnet and omphacite separates. The samples yield Lu-Hf ages ranging from 101.79 ± 0.92 Ma to 89.89 ± 0.37 Ma. Exception are the two-phased garnets in the eclogite from Texel complex, which give an apparent Triassic age, indicating a variable mixing of Alpine and pre-Alpine (Variscan or Permian) garnets. Investigation of the major and trace elements distributions in garnets all other samples show typical prograde growth zoning during increasing pressure and temperature, with high Mn and/or Lu concentrations in the garnet cores compared to their rims. Therefore, the obtained ages are interpreted to be related to burial during subduction.

In summary, combining pre-existing data with the new structural, petrological and geochronological constraints suggest that (1) subduction of the Austroalpine high-pressure belt lasted from ~100 to ~90 Ma, (2) eclogites from the Texel complex represent re-subducted older (pre-Alpine) garnet-bearing metabasic rocks, and (3) the earliest-subducted Eoalpine rocks are found in Koralpe and Saualpe. These new results represent important constraints for the construction of a kinematic model for Eoalpine subduction.

*Janák, M. et al. 2015. J Metamorph Geol, 33: 495–512.*

Talk

## What field geology, P-T modeling, and garnet geochronology can tell about subduction and exhumation

**Thorsten Nagel**

*Aarhus University, Denmark*

Some of the most controversial questions in orogeny that have partly been discussed for decades, concern high-pressure/ultra-high-pressure (HP/UHP) tectonic units: Are these units accreted from subunits with very different pressure-temperature (PT) histories or do they represent coherent pre-subduction bodies? Did high-pressure rocks possibly experience very complicated metamorphic histories reflecting multiple subduction-exhumation cycles in a few million years? And do metamorphic pressures derived by equilibrium thermodynamics represent “depth-convertible” lithostatic conditions at all?

I review key observations, concepts, and open questions in oceanic and continental HP/UHP nappes with a focus on the Cenozoic Alps. A recurring scheme is that complex scenarios (several subunits/multiple subduction cycles/ protracted histories) are often proposed in studies using isotopic dating of accessory minerals combined with trace element and inclusion data. More classic approaches such as the derivation of pressure-temperature histories from main metamorphic assemblages and mineral zoning often suggest more conventional PT loops although minerals like garnet, pyroxene, or amphibole as well as reaction microstructures should be capable of recording complex histories and occasionally do so. Accordingly, garnet ages typically support straight subduction-exhumation scenarios at least in single samples. I propose that mapping metamorphic field and age gradients in HP/UHP units, though work intensive, might be the critical approach to test scenarios. HP assemblages as a result of local stress concentrations or multiple subduction events are difficult to harmonize with consistent field gradients.

In the Cenozoic Alps, nappes derived from the subducted European margin (e.g. Eclogite Zone in the Tauern Window, Adula Nappe in the central, Internal Massives in the western Alps) seem to represent more or less coherent pre-subduction basement slivers that experienced a rapid and single subduction-exhumation cycle in the late Eocene. The mixed oceanic-continental HP/UHP units of the western Alps appear to be accreted from units that were subducted at different times although they record similar low geothermal gradients. Especially the small continental slivers stranded in the oceanic Zermatt-Saas Zone and the continental Sesia Nappe on top exhibit scattering HP ages, partly even within a single sliver. Nevertheless, overall increasing ages are observed towards higher structural positions. If these units did not experience multiple subduction cycles, some of them they must have stayed at great depth for several millions years without getting substantially heated.

Talk

## Alpine (U)HT metamorphism in the Gruf Complex: which consequences for the evolution of the Central Alps?

**Jeff Oalmann[1], Erik Duesterhoeft[2], Andreas Möller[3], Romain Bousquet[2]**

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Understanding the thermal evolution (i.e. the timing, rate, duration…) within mountain belts has important implications for the geodynamic evolution of both ancient and modern orogenies. Ultra-high temperature metamorphism requires geodynamic or tectonic processes that bring excess heat. Therefore, dating UHT metamorphism can shed light on the geodynamic evolution of the geological settings in which UHT rocks are exposed.

Using an in-situ approach, this study combines accessory mineral U-Pb geochronology with thermobarometric modeling to elucidate the P-T-time (P-T-t) evolution of sapphirine-bearing granulites from the Gruf Complex in the Central Alps. Several questions are addressed: (1) When did the Gruf Complex experience UHT metamorphism? (2) What part(s) of the P-T evolution HT rocks can be dated using accessory phase U-Pb geochronology? (3) What kind of geodynamic processes are producing (U)HT metamorphism? (4) How this process may take place in the Central Alps models?

Equilibrium phase diagrams and *in situ* U-Pb dating indicate that the granulites underwent UHT metamorphism > 900 around 1.0 GPa after decompressing from ca. 800°C and 12 GPa. This decompression-heating event resulted in the breakdown of garnet to form orthopyroxene, sapphirine, and cordierite. A lack of inherited monazite and presence of young (34–30 Ma) monazite within UHT textures is interpreted to indicate that UHT metamorphism was the last main metamorphic the Gruf granulites experienced. Textural observations and Ti-in-zircon thermometry reveal that minor zircon growth occurred in equilibrium with garnet around 35 Ma, and zircon was not growing, but resorbing during UHT metamorphism, and thus the youngest zircon rims are used to date post-UHT melt crystallization and cooling at 32.7 ± 0.7 Ma. The U-Pb zircon ages of variable deformed felsic dikes indicate that the lower crustal UHT rocks were juxtaposed against the midcrustal migmatites between 30 and 27 Ma and contractional deformation ceased by 25.6 ± 0.3 Ma in the Gruf Complex. Finally, U-Pb rutile ages indicate that the amalgamated Gruf Complex cooled over an 11 Ma period from 30 to 19 Ma.

In classical models for the Central Alps, the Gruf massif is considered as the distal extension of the Adula massif (European continent). No evidence of HP metamorphism has been documented in the Gruf massif and no HT metamorphism in the Adula massif. Taking into account our results, we propose to discuss on one hand possible scenarii for the late evolution of the Central Alps and on another hand paleogeographic origin of the different units.

Talk

## Evidence of large-scale Mesozoic detachments preserved in the basement of the Southern Alps (northern Lage di Como area)

**Christophe Real[1], Nikaulos Froitzheim[2], Rodolfo Carosi[1], Simona Ferrando[1]**

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A polyphase metamorphic basement crops out in the northern part of the South Alpine domain of the Alps (Spalla *et al.,* 2000). It is involved in Alpine tectonics and locally overprinted by low-grade Alpine metamorphism. Pre-Alpine and Alpine events must be distinguished in order to reconstruct the tectonic evolution. We investigated Pre-Alpine structures in the basement of the northern Lago di Como area with the aim to identify rift-related faults.

The well-known Lugano Val Grande Fault (LVGF) has been taken as an example in order to identify other detachments preserved in the studied area (Bertotti 1991, Bertotti *et al.,* 1993). We investigated the tectonic contacts between Triassic carbonates and the Variscan basement in the Domaso-Cortafò Zone, south of the Insubric line. We identify for the first time the Sasso Pelo Detachment (SPD), forming the base of the Triassic succession and characterized by the superposition of carbonatic breccias without basement clasts above basement mylonite. The SPD displays the same structural characteristics as the LVGF, partitioning of the deformation mechanism along the fault zone, *i.e.* brittle structures in the hanging wall and ductile deformation in the footwall. Mylonites are found only in the footwall, both in micaschists and paragneisses. Cataclasites occur only in the hanging wall, at the base of the sedimentary breccias. The fault likely accommodated a large displacement because we find the juxtaposition of brecciated sedimentary rock directly above the mylonitic basement, as observed for the LVGF. The sense of transport along the SPD is top-to-the-West, opposite to the more southerly located LVGF (top-to-the-East). This may reflect a lateral polarity change in Mesozoic rift architecture, or, alternatively, a significant Alpine displacement along the Musso Line, a steep fault between the two detachments.

Our results demonstrate the occurrence of major pre-Alpine, post-Variscan crustal detachments. They were folded during the Alpine orogeny and partly eroded but are generally well preserved.

Bertotti, G., Seward, D., Wijbrans, J., ter Voorde, M., Hurford, A.J. (1999): Crustal thermal regime prior to, during, and after rifting: A geochronological and modeling study of the Mesozoic South Alpine rifted margin. Tectonics, 18, 185-200. Spalla, M.I., Siletto, G.B., di Paola, S., Gosso, G. (2000): The role of structural and metamorphic memory in the distinction of tectono-metamorphic units: the basement of the Como lake in the Southern Alps. J. Geodynam., 30, 191-204.

Talk

## Kinematic evolution of the Paleoproterozoic Kynsikangas ductile shear zone, SW-Finland

**Sebastian Reimers**[1], **Jon Engström**[2], **Ulrich Riller**[1]

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The Kynsikangas Shear Zone (KSZ) belongs to the few prominent, crudely N-S striking ductile deformation zones within the generally E-W striking structural grain of the Svecofennian Orogen in SW Finland. In order to assess the tectonic significance of the KSZ in this orogen, knowledge of the overall deformation regime and kinematic evolution of the shear zone is necessary. Here we present the results of a detailed field-based structural analysis of the Kokemäki segment of the KSZ. This segment lends itself also to elucidate the reliability of small-scale kinematic indicators in assessing the overall sense-of-shear inferred, for example, from the km-scale foliation pattern.

Based on the orientation of mineral foliation (S) and lineation (L) in metagranitoid rock and migmatite, the Kokemäki segment can be devided into and an eastern, a central and a western zone. The shear zone center is characterized by prolate (L>>S) mineral shape fabrics with sub-horizontal $E_1$-axes (where $E_1 \geq E_2 \geq E_3$). By contrast, the eastern and western zones are marked by S > L fabric geometry with moderately to steeply plunging $E_1$-axes. The km-scale curvature of foliation surfaces points to an overall left-lateral sense-of-shear during ductile deformation. However, shear sense based on small-scale kinematic indicators, notably C-S fabrics, rotated rigid objects and asymmetrically folded metamorphic layers are at variance with the first-order kinematics of the KSZ. This holds in particularly for stations with known $E_1$-axis orientations and shear directions inferred from C-S fabrics, showing large angular departures between the two.

Collectively, the structural and kinematic observations lead us to conclude that the KSZ experienced at least two kinematically different deformation regimes, where horizontal ductile stretching was followed by subvertical sense-of-shear indicated by C-S fabrics. We also conclude that small-scale kinematic indicators, now routinely used as criteria for the determination of shear-zone kinematics, may not provide reliable information in this regard. Finally, despite complex internal ductile flow, evident by the spatial variation in S - L fabric geometry and kinematics of C-S fabrics, the KSZ seems to have accommodate a strong component of left-lateral transpression.

Talk

## Do Paleozoic basement structures affect present-day stress orientation in central Western Europe?

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The in-situ stress state of the Earth’s crust is under investigation since decades for both, scientific and economic purposes. Several methods have been established to indicate the present-day orientation of the maximum compressive horizontal stress ($S_{Hmax}$). It is assumed that the same forces that drive plate motion are the first order stress sources and one could presume that $S_{Hmax}$ is always parallel to plate motion, which is the case for some regions. However, deviations from this general trend occur in many regions. Therefore, second and third order sources of stress have been identified that potentially cause regional and local stress rotation with respect to the long wave-length trend imposed by plate tectonic forces. One group of such subordinate stress sources are lateral heterogeneities in the crust, based on density, petrothermal or petrophysical properties, or discontinuities like faults or low-viscous horizons, which lead to stress rotations or stress field decoupling.

The World Stress Map (WSM) project compiles systematically stress orientation data of the present-day $S_{Hmax}$ orientation. The increasing amount of stress orientation data allows to investigate areas with consistent stress rotation, divergent to the regional stress pattern. In our work, we analyse the stress pattern variability and its causes in several parts of Europe.

The exhibit fan-shaped $S_{Hmax}$ orientation pattern in the Alpine foreland and the Carparthian Mountains are perpendicular to the trend of the mountain chain and can be explained as a consequence of gravitational potential energy of the orogen. However, many regions in central Western Europe exhibit $S_{Hmax}$ orientation pattern, that are neither to explain by present-day plate tectonic, nor recent orogens. Western Europe is a record of a polyphase Paleozoic (and earlier) deformations. We compare Caledonian and Variscan suture zones and mega-structures with the observations of the present-day crustal stress. There are several areas, where the observed $S_{Hmax}$ pattern follows Paleozoic structures. Both is observed, that $S_{Hmax}$ is parallel or perpendicular to the basement structures. This appears to be inconsistent from the first view, which is not the case, as lateral heterogeneities or discontinuities in the crust are able to align both, $S_{Hmax}$ as well as the minimum horizontal stress ($S_{hmin}$) orientations, which are always perpendicular to each other. Therefore, petrophysical heterogeneities can be expected as reason for the observed stress rotation. Large contrasts of the Young’s modulus and low-friction faults can be identified as potential regional stress sources in the Paleozoic basement in Western Europe.

Poster

## Structural framework of the 1979 Mw 7.1 Montenegro earthquake

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The southern Adriatic Sea and the border area between Albania and Montenegro provide a rare example of active continental subduction at the junction between the Dinarides and Hellenides fold-and-thrust belts. The deformation front accommodates c. 4 mm/yr of convergence (Jouanne *et al.*, 2012). In 1979, it hosted one of the strongest instrumentally recorded earthquakes in Europe offshore the city of Bar, Montenegro ($M_w$ 7.1, Benetatos and Kiratzi, 2006). The area is characterised by pronounced along-strike changes, which were kinematically induced by a southward increasing rollback of the Aegean slab and concomitant upper-plate extension. In spite of the abundant seismotectonic and a growing amount of geodetic data in that area, no satisfying structural model exists for this complicated zone yet. We combined onshore and offshore data as well as cross section balancing approaches to improve the structural framework in the 1979 epicentral area.

Both onshore and offshore units in the 1979 epicentral area are characterised by southwest-vergent nappes. Going from hinterland to foreland, these are the Budva (or Krasta-Cukali) and the Dalmatian (or Kruja) thrust units. While the Budva unit contains a mid-Triassic to Eocene, dominantly pelagic succession, the Dalmatian unit comprises Early Cretaceous to Oligocene neritic carbonates and synorogenic turbiditic siliciclastics. The basal detachment of the Dalmatian unit contains evaporites of likely Early Cretaceous age, which are only known from subsurface exploration. On- and offshore data from both Albania and Montenegro imply (1) that the Dalmatian unit is subdivided into 3 to 4 thrust imbricates and (2) that thrusting was largely accomplished before mid-Miocene times, as evidenced by a wide-spread unconformity on top of the thrusts. Post-mid Miocene shortening along these imbricates is very minor in our study area. Reflection seismic data show that the Dalmatian basal detachment, at a depth of c. 4 to 6 km is folded into a gentle antiform with a wavelength of c. 10-20 km and an amplitude of c. 1-2 km (Bega and Schleder, 2017). This implies post-mid-Miocene contraction on structurally lower thrusts underlying the Dalmatian Zone. This "infra-Dalmatian" thrust unit corresponds to the Ionian Zone, which has no surface exposures anywhere north of Central Albania. Several wind gaps in anticlines in the Dalmatian Zone suggest Plio-Quaternary surface uplift of the coastal regions. In combination with the young antiform observed in the subsurface data, this implies ongoing thrusting along infra-Dalmatian thrusts. We also suspect that the 1979 earthquake was triggered by motion along one of these thrusts.

**References**

Benetatos, C., Kiratzi, A., 2006. Finite fault-slip models for the 15 April 1979 (Mw 7.1) Montenegro earthquake and its strongest aftershock of 24 May 1979 (Mw 6.2). *Tectonophysics* 421, 129-143.

Bega, Z., Schleder, Z, 2017. Review of Mesozoic Exploration Plays in the Montenegro – NW Albania Segment of South Adriatic Basin. *AAPG Annual convention and Exhibition, Huston, Texas, April 2-5. Search and Discovery Article #90291*.

Jouanne, F., Mugnier, J.L., Koci, R., Bushati, S., Matev, K., Kuka, N., Shinko, I., Kociu, S., Duni, L., 2012. GPS constraints on current tectonics of Albania. *Tectonophysics*, 554+557, 50-62.

**Poster**

## Cenozoic Exhumation and Fault Activity of the Western Eger Rift, Czech Republic, from Low Temperature Thermochronology

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The Eger Rift and Cheb Basin in northwestern Bohemia are part of the European Cenozoic Rift System. They are dominant features of the local topography and are associated with earthquake swarms, voluminous $CO_2$ outgassing and Quaternary mantle-derived volcanism. The Eger Graben, of which the Cheb basin is considered a subbasin, contains a Cenozoic volcano-sedimentary record no thicker than 500 m. The main graben structure is delineated by two faults: (1) the ENE-striking Krušné Hory Fault (KHF), which delimits the northwestern shoulder of the Eger rift and has accommodated tilting and uplift of the Krušné Hory (Erzgebirge), creating a present day elevation difference of 700 m and (2) the České Středrohoří Fault (CSF) which separates the basin from the southern rift shoulder. A third major fault, (3) the NNW-striking Mariánské Lázně Fault (MLF) perpendicularly cross cuts these two faults, forming the boundary to the Cheb basin. Yet despite their importance for the formation of the local topography, the exact time of onset of fault activity, fault offset and total exhumation of the resulting shoulders remains unclear. We we have tested whether low-temperature thermochronology is able to constrain the Cenozoic exhumation of the rift shoulders and the timing of rift shoulder uplift . We present a new apatite (U-Th)/He dataset (AHe), the first from the Czech part of the Erzgebirge, consisting of three vertical profiles: one on each shoulder of the Eger Graben and another crossing the MLF from the Cheb basin onto the elevated plateau of the Slavkovský Les Mountains (Kaiserwald). In combination with geochemical and sedimentological results our data reveal how basement surfaces in the Krušné Hory and Slavkovský Les were planated and formed one single granitic plateau already at the end of the Cretaceous. Thermal models of our AHe data prove a maximum exhumation of 1-1.5 km since then, unlike the surrounding areas which, based on previous apatite and zircon fission track studies, have experienced 1.5-5.6 km of Tertiary denudation. Rift formation occurred in the late Oligocene and fault offsets were small, a few hundred meters at the most, as no definite difference in AHe ages was found across either of the faults or with increasing elevation.

Talk

## Tectonics of the Krušné hory Fault (Czech Republic): observations from broken-plate flexure models

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The Eger Rift and Cheb Basin in northwestern Bohemia are part of the European Cenozoic Rift System. They are dominant features of the local topography and are associated with earthquake swarms, voluminous $CO_2$ outgassing and Quaternary mantle-derived volcanism. The main graben structure is delineated by two faults: (1) the ENE-striking Krušné Hory Fault (KHF), which delimits the northwestern shoulder of the Eger rift and has accommodated tilting and uplift of the Krušné Hory (Erzgebirge), creating a present day elevation difference of 700 m and (2) the České Středrohoří Fault (CSF) which separates the basin from the southern rift shoulder, creating a present day elevation difference of 250 m. A third major fault, (3) the NNW-striking Mariánské Lázně Fault (MLF) perpendicularly cross cuts these two faults, forming the boundary to the youngest subbasin, the Cheb basin. The Eger Graben contains a Cenozoic volcano-sedimentary record no thicker than 500 m. Overall the short lifespan and low subsidence rates rather imply a failed, incipient rift. As widely accepted, the Erzgebirge uplift in Plio-Quaternay times ensues the rift formation (Eocene to Pliocene), but it can be stated that the relation between rift formation and Erzgebirge uplift is not yet fully understood. Yet despite their importance for the formation of the local topography, the exact time of onset of fault activity, fault offset and total exhumation of the resulting shoulders remains unclear. The ENE-striking rift systems axis roughly parallels a major crustal inhomogeneity, interpreted as a Variscan suture between the Saxothuringian and Tepla-Barrandian/Moldanubian zones, reactivated in Cretaceous/Tertiary times due to Alpine orogeny. The flexural models assume a weak zone in the lithosphere (e.g. break), which might coincide with the Variscan plate boundary (Saxothuringicum-Moldanubicum). Broken-plate flexure modelling is an approach to unravel Erzgebirge uplift, match basin geometries and delimit applied forces. The models can reproduce the asymmetric subsidence and shoulder uplift of the Eger Rift, which might be explained by a slightly thicker crust, 3-5 km, or a thinner mantle lithosphere under the Erzgebirge and Eger Rift. Seismic profiles across the Eger Rift express P-wave velocity contrasts, interpreted by previous authors as high-velocity bodies due to magmatic underplating (Mullick et al. 2015, Hrubcova et al. 2017). We assume that the late reactivation of the break in Oligocene time may reflect the loss of a sub-crustal load (remnant slab?) induced by e.g. mantle upwelling.

Talk

## Influence of mechanical stratigraphy and pre-existing structures on fold-thrust-belt geometry

**Christoph von Hagke[1], Michael Kettermann[1], Prokop Zavada[2], Kathrin Mothe[1], Dominik Gottron[1], Janos L. Urai[1]**

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Foreland fold-and-thrust belts are well-explored and intensively studied parts of orogenic systems worldwide. A general result of these studies is that it is not only of critical importance to understand individual structures and thrust belt geometries, but also to untangle the sequence of thrusting and tectonic events, and furthermore that also kinematic solutions should at best be substantiated with mechanical models. Two factors influencing thrust belt geometries that become more and more recognized are 1) mechanical stratigraphy of the sedimentary pile involved in thrusting, and 2) the role of a change in structural style form thin- to thick-skinned tectonics.

In this contribution we address these two parameters using scaled physical models. A first set of analogue experiments was performed in the laboratory of the Institute of Geophysics of the Czech Academy of Science in Prague. With this experimental series we particularly test the influence of changing detachment rheologies with the ultimate goal to produce backthrust-dominated fold-and-thrust belts. In the second set of experiments, performed at RWTH Aachen, we test the impact of the thick-skinned deformation on earlier thin-skinned tectonics.

Results show both parameters exert strong control on fold-and-thrust belt geometries. As opposed to previous suggestions, a rapid change in detachment rheology does not necessarily result in backthrusting at the orogenic front. However, behind the orogenic front, a back-stepping sequence of foreland verging thrusts may occur, if the rheological contrast within the detachment is large enough. Secondly, thick-skinned reactivation of thin-skinned structures only partly localizes on pre-existing faults. The degree of reactivation depends on thrust spacing of the thin-skinned part, as well as on the shape of the overlying wedge. We compare our results to the fold-and-thrust belt of the Central Alps and the Carpathians.

Poster

## 3D surface reconstruction and analysis of massively dilatant faults in Iceland

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Massively dilatant faults (MDF) develop in cohesive rocks under small differential stresses, for example close to the Earth's surface at rift zones but potentially also at depth. The formation of MDF implies the existence of large cavities in the sub surface that may be interconnected. Thus, these structures are of great importance for fluid transport in the upper crust. However, knowledge on their 3D geometry, dilatancy at depth and interconnectivity is sparse. In this contribution we present an extensive high-resolution geomorphological dataset, which we use to describe MDF geometries in 3D with the ultimate goal to better understand their evolution.

Iceland is an ideal area to study MDF, as it offers exquisite outcrop conditions of a Mid Ocean Ridge. Furthermore, it is possible to observe MDF in different kinematic settings: Rift perpendicular in the Northern and oblique extension in the Western Rift Zone. We apply unmanned aerial vehicles combined with Structure from Motion software to generate 3D point clouds and digital elevation models of their surface expressions. To overcome the limited point cloud density at exposed vertical fault planes, we extended some models with further measurements with a terrestrial laser scanner (TLS). As not all MDF allow the positioning of a TLS between the fault planes, we used additional photographs taken with DSLR cameras to aid the model creation.

Due to model size and detail, these datasets offer unprecedented insights into the geometry of fault and fracture surfaces at scales from few centimeters to kilometers. Our detailed mapping reveals a large variety of different structures occurring at MDF, such as tilted blocks, open fractures, relays, segment nodes or fault branches. Additionally, MDF develop across lithological changes, are filled with different materials (e.g. lava, sand, ice), which sometimes are indicative for interconnections at depth. We evaluate spatial distributions of observed features and measure orientation, opening width, offset, and fracture density. With the extracted information, we are able to characterize and define fracture and fault types, highlight geometrical relationships and correlations of different parameters.

In combination with results from scaled analog models we can show that common measures of dilatancy at rift settings are overestimated. Furthermore, MDF reach far deeper than current models predict. These findings have direct implications for our understanding of the kinematics and mechanics of rift zones on Earth.

**Poster**

## Three-dimensional modelling of the Eastern Alps

**Davood M. Yosefnejad, Thosten J. Nagel, Nikolaus Froitzheim**

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The tectonic evolution of the Eastern Alps involved subduction and collision processes during the Mesozoic and Cenozoic and resulted in a complicated structure at the surface where tectonic nappes are exposed, but also at depth where subducted lithospheric slabs appear to dip in different directions. The structure is highly three-dimensional and not completely understood. In this research we have tried to integrate all available data such as DEMs, geological maps, profiles from different sources as well as 30 newly constructed cross-sections in order to build a comprehensive 3D model for this complex area by using a GIS data base and the modelling software MOVE (Midland Valley Co.). The model allows us extracting cross-sections in any desired orientation, determining volumes of tectonic units, line and area balancing for all the profiles, and geophysical modelling. In the first step, we have analysed the profiles and calculated the amount of shortening for all the profiles. We have considered top of European and Adriatic basement as a reference for calculating the amount of shortening for European and Adriatic continents. Line balancing of the European basement shows ~100 km shortening in the West (NFP20 East), a decrease to ~50 km in the Engadine Window, an increase towards east to a maximum of ~140 km in the western Tauern Window, and a decrease to rather constant values of ~80-90 km further east. Area balancing assuming constant pre-collisional crustal thickness gives generally lower values for shortening than line balancing and even negative values east of the Tauern Window (i.e. stretching), which may reflect, among other processes, pre-orogenic thinning of the continental margins as well as east-west stretching of the crust during Miocene tectonic extrusion. Line balancing of shortening of the South Alpine basement gives values of ~50 km in the West (NFP 20), a maximum of ~65 km, close to the western end of the Tauern Window, and a strong decrease towards east reflecting the transfer of shortening of Adria from the Southern Alps to the Dinarides. The added shortening of European and South Alpine basements is at a maximum at the western end of the Tauern Window, probably reflecting pre-Alpine margin geometry (Dolomites indenter). Although the model carries large uncertainties, partly due to the scarcity of information about deep crustal structure away from the seismic sections, these results are in good accordance with the tectonic evolution as inferred from other methods.

**Poster**

## The Yuli Belt in the eastern Taiwan fold-and-thrust belt: A Miocene accretionary prism separating Eurasian and Philippine Sea Plates

**Yiqiong Zhang[1], Nikolaus Froitzheim[2], Chin-Ho Tsai[3], Kamil Ustaszewski[1]**

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The Taiwan orogen is a consequence of the oblique subduction of the Eurasian continental margin below the Luzon volcanic arc of the Philippine Sea Plate (Suppe, 1981). The Yuli belt (YB) of the eastern Central Range, exposed in the retro-wedge of the Taiwan fold-and-thrust belt, hosts blueschist-facies igneous rocks tectonically emplaced into a mostly greenschist-facies and intensely deformed metasedimentary succession (Tsai et al. 2013). It has long been considered as an exhumed portion of the distal passive margin of Eurasia. However, recently obtained geochronological data call for a reinterpretation. Lu-Hf-dating of a blueschist-facies igneous rock yielded 5.1 +/- 1.7 Ma (Sandmann et al., 2015). U-Pb zircon dating in both igneous and metasedimentary rocks (Chen et al. 2017) yielded ages as young as c. 15 Ma. Next to providing a possible crystallization age for the HP-rock protoliths, these findings imply that the succession received detrital input well into the Miocene. The Yuli Belt should, therefore, be reconsidered as a Miocene accretionary prism. However, numerous aspects of the tectonics of the Yuli Belt remain unclear. The kinematics of the tectonic contact with the westerly adjacent Tailuko schists (Shoufeng Fault) are unknown. Also, the metamorphic conditions reached in the metasedimentary units are poorly constrained.

From our field work and microstructural analysis, the exposed YB schists were affected by five deformation phases. D1 involves west-vergent thrusting and folding with the development of slaty cleavage and E-W stretching lineation marked by chlorite-mica aggregates. D2 is top-E back-thrusting and associated folding with W-dipping axial planes and crenulation cleavage. D3 produces folding and crenulation with east- to northeast-dipping axial planes, possibly related to the westward thrusting of the Coastal Range, and D4 is another phase of weak folding with subhorizontal axial planes. D5 accommodated minor N-S extension by normal faults. The transition between the YB and the Tailuko schists to the west is gradual and structures are similar on both sides; it appears that the juxtaposition of YB and Tailuko belt occurred already during D1. Further work is necessary to constrain the deformation-metamorphism relations and the exhumation mechanism of YB blueschists.

Suppe, J., 1981, Geological Society of China Memoir 4, p. 67–89.

Tsai, C.H., Iizuka, Y., Ernst, W.G., 2013, J. Asian Earth Sci. 63, 218–233.

Sandmann, S., Nagel, T.J., Froitzheim, N., Ustaszewski, K. & Münker, C., 2015, Terra Nova, 27, 285-291.

Chen, W.-S., S.-L. Chung, H.-Y. Chou, Z., et al., 2017, Tectonics, 36, doi:10.1002/2016TC004383.

# Topic 3: Mountain building from depth to surface

## 3a) “Investigating mountains with a microscope”: How microscale studies contribute to the understanding of mountain building processes

Talk

### Evidence for post-Variscan partial melting of amphibolites in the Strona-Ceneri Border Zone (Lago d’Orta, northern Italy)

**Stefano De Bernardi[1], Simona Ferrando[1], Alessandro Decarlis[2], Alessandro Borghi[1], Gianreto Manatschal[2]**

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Melting of basic rocks occurs at high P-T gradients, e.g. during Archean times or during exhumation of hot UHP rocks. The basement of the Southern Alps well records the Variscan metamorphic evolution without evidence of the subsequent Alpine metamorphism. Here, we report the tectono-metamorphic evolution of a coarse-grained amphibolite from the area near Omegna and Pella (western side of the Orta Lake). The rocks belong to the Strona-Ceneri Border Zone (SCBZ), a transitional level located between Strona-Ceneri Zone meta-arenites and Scisti dei Laghi meta-pelites. It consists of banded amphibolites and paragneisses with relict lenses interpreted by previous authors as pre-Alpine ophiolites (ultramafics, metagabbros from MORB tholeiites, and retrogressed eclogites).

A detailed petrographic study of coarse-grained amphibolites reveal the presence of relic amphiboles of the former ophiolitic gabbro, a pre-kinematic Amp+Pl+Qz+Ilm mineral assemblage, and a syn-kinematic (Variscan regional foliation) Amp+Pl+Qz+Ttn±Bt mineral assemblage. Evidence for post-kinematic partial melting is given by peritectic Amp, Cpx, Pl, Qz, Ilm, and by pods and interstitial aggregates of Pl±Qz±Bt±Amp. A last event generates titanite, sericite and saussurrite.

The P-T pseudosection for MORB allows to define: i) the P-T conditions for the syn-kinematic mineral assemblage, that are in agreement with previous data for the Variscan Carboniferous event at amphibolite-facies conditions, ii) the isobaric increase of temperature up to 780°C during the partial melting event. This thermal event produced both a Sil+Kfs mineral assemblage and intrusions of undeformed aplites in nearby para- and orthogneisses. The related temperatures were significantly higher than those calculated by previous authors for the partial melting event generated by the Permian intrusions along the Cossato-Mergozzo-Brissago line or by the proximity of a »hot« Ivrea-Verbano Zone. On the contrary, these rocks occur near the Pogallo line, responsible for an amphibolite-facies milonitic event, which microstructures overprint those generated by the partial melting. In the westernmost part of the Southern Alps (NW Italy) anomalously high, Late Triassic/Early Jurassic thermal gradients, connected with the Alpine Tethys rifting, have been recently suggested. This area corresponded to the transition from the proximal to the distal part of the Adriatic margin, where the necking fault system localized (Pogallo line p.p.). Thus, our work reveals petrological evidence for the presence of a post-Variscan high-temperature event, able to melt the basic rocks of the intermediate crust, localized in the area that was later affected by the necking fault system.

Poster

### Decoding Rare Earth Element (REE) patterns in HP/LT garnets

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Due to its inertion to recrystallization and reequilibration, garnet is well-known for its ability to preserve rock-forming processes which occurred during its growth. In order to interpret preserved growth zonation it is important to distinguish between kinetically- and equilibrium-controlled processes that led to changes of garnet’s composition. A combined investigation of major and trace elements is ideal to unravel a garnet’s history, as small ions (Mn, Mg, Fe) are mobile via intra-crystalline diffusion, and could even reset garnet composition if sufficient conditions are met; and large ions (Ca, REE) in garnet are immobile on a thin section scale and can be incorporated only by reaction with REE-rich mineral phase. Modern analytical techniques allow visualization of compositional features down to the nanoscale.

Here we present high-resolution major and trace element mappings that demonstrate the following end-member cases: (i) the garnet from the Dominican Republic blueschist preserve three HREE reaction-enrichment events, followed by oscillatory zoning at the rim and later manganese back-diffusion. Careful comparison of inclusion suite with the detailed 2D trace element mappings allows correlation of the REE pattern with the reaction path of the sample.

(ii) In a second set of samples from the Western Alpine Sesia Zone, the comparison of REE mappings with orientation contrast mappings exhibits two main features: small ions diffuse into and along subgrain boundaries and whereas Ca+REE are uneffected by later diffusion equilibration. This leads to a decoupling of small ions, such as Mn, Mg, Fe, from large ions like Ca and REEs. Such decoupling can lead to a significant misinterpretation of compositional growth zonations with respect to a reaction path of a sample.

Talk

## Regional pyroxene hornfels overprint in Variscan rocks - short lived melting events deduced from diffusion modelling in garnet

**Lars Erpel**

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Anatectic metapelitic granulites have been investigated from the Moldanubian zone of the Bohemian Massif (Winklarn, NE Bavaria). Associated metabasic rocks (former eclogite) show evidence for a short-lived LP – HT pyroxene hornfels event at 4 – 6 kbar that followed subduction and exhumation (Scott et al. 2013). Unusual gedrite- and orthopyroxene-bearing rocks from the same location also point to HT-LP conditions. Most metapelitic rocks in this area exhibit LP – HT parageneses i.e., biotite – plagioclase or cordierite – sillimanite – K-feldspar. However, rare porphyroblastic garnet occurs in some samples set in a matrix of fibrolitic sillimanite, different generations of cordierite, K-feldspar and biotite. In the largest garnets, multiple cores ($Alm_{59}$ $Py_8$ $Gro_{12}$ $Sps_{21}$) have merged during prograde growth. Subsequent growth proceeded as a series of incomplete shells ($Alm_{68}$ $Py_{18}$ $Gro_9$ $Sps_5$). Inclusions in garnet cores are kyanite, rutile and staurolite, whereas biotite, plagioclase and melt inclusions can be found in the overgrowth shells. The LP-HT stage in these rocks is reflected in 1) melt patches containing idiomorphic cordierite, fibrolite and K-feldspar 2) embayments in biotite +/- spinel 3) reaction of "inclusions" in garnet yielding corundum +/- quartz +/- spinel after kyanite and staurolite and 4) extremely sharp diffusion zoning (demonstrably not resorption) at some garnet rims despite garnet consumption elsewhere in the same thin section. Modelling shows that Mn diffusion into garnet took place over a very short period of time (<< 1 Ma) for even the most conservative temperatures. Tectonothermal models involving crustal stacking and internal heating of the crust cannot explain this short time scale, as they operate on time scales of tens of millions of years. A regional contact metamorphism fits the timescale much better although the Variscan granites cannot be the heat source. Evidence is mounting that exhuming underplated continental crust, as exposed in the UHT granulite complexes of the Variscan basement (Bohemian Massif, Black Forest, Vosges, Massif Central) is the advective heat source (as already suggested by O'Brien 2000).

Scott, J. M.; Konrad – Schmolke, M.; O'Brien, P. J.; Günter, C., High – T, Low – P Formation of Rare Olivine – bearing Symplectites in Variscan Eclogite, J. of Petrology (2013) 54 (7): 1357 – 1398

O'Brien P J, The fundamental Variscan problem: high-temperature metamorphism at different depths and high-pressure metamorphism at different temperatures, Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geological Society, London, Special Publications, 2000, vol. 179 (pg. 369-386)

Poster

## Crustal melting in the Bohemian Massif: a treasure chest full of nanogranitoids

**Silvio Ferrero[1,2], Patrick J. O'Brien[1], Alessia Borghini[1], Bernd Wunder[3], Markus Wälle[4], Christina Günter[1], Martin A. Ziemann[1]**

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The central European Bohemian Massif has undergone over two centuries of intense scientific investigation which has made it a pivotal area for the development and testing of modern geological theories. The discovery that deep melts can be preserved in natural rocks as melt inclusions, either crystallized (i.e. as nanogranitoids) or as glass, prompted the re-evaluation of the Bohemian Massif with an "inclusionist" eye.

Former melt inclusions can be confidently identified in thirteen localities spanning the whole massif. Most of the findings are from the Moldanubian zone with seven localities (Althütte, Stückstein, Winklarn quarry, Plešovice quarry, Ktiš, Kutná Hora Complex and Dunkelsteinerwald in the Gföhl Unit), the Granulitgebirge with three findings (Mohsdorf, Rubinberg/Klatschmühle and Waldheim), the Polish Sudetes with two occurrences (Orlica-Snieznik and Gory Sowie), one in the Erzgebirge area (Forchheim near the Saidenbach reservoir) and one from the T7 borehole south of the Erzgebirge area (Staré in the České středohoří Mountains). The host rocks are extremely variable, encompassing felsic and/or perpotassic granulite, stromatic migmatite/paragneiss, eclogite and garnet clinopyroxenite. The conditions of melt entrapment, which corresponds to the garnet formation conditions, span the whole field of high temperature metamorphism, from 800°C and 0.5 GPa in the metasediments of Althütte to >1000°C and 4-5 GPa in the Erzgebirge. This contribution provides an overview of such melt inclusions and explains the multiple constraints they provide for crustal melting. Qualitative constraints are discussed targeting both the partial melt and the COH fluids often present during melting at depth. Crucial quantitative information on the geochemical signature of deep melts can be derived from nanogranitoid studies, a fundamental aspect for unravelling the incongruent melting reactions responsible for the formation of anatectic melt and thus better understanding the geodynamic history of the crust. Novel constraints on the mutual stability of melt and host garnet are generated as an intriguing by-product of our re-homogenization experiments on natural nanogranitoids.

Overall this work aims to generate microstructural guidelines and provide methodological suggestions for petrologists wishing to explore the fascinating field of melt inclusions in metamorphic terranes worldwide, based on the newest discoveries from the still enigmatic Bohemian Massif.

Poster

## Melting in high-pressure granulite-facies metapelites from a 2 Ga old subducted oceanic crust: evidence from polymineralic inclusions

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Partial melting events in metamorphic rocks can sometimes only be detected by the occurrence of polymineralic inclusions representing a crystallized melt. Polymineralic inclusions have been found in garnet porphyroblasts of metapelites from the Usagaran Belt, Tanzania. The metapelitic mineral assemblage garnet+kyanite+ternary feldspar+quartz+biotite indicates high-pressure granulite-facies conditions. The metapelites are associated with eclogites and marbles, representing an ancient subducted oceanic crust (Möller et al. 1995). The polymineralic inclusions indicate partial melting of the oceanic crust and are therefore distinct from other occurrences of polymineralic inclusions for which partial melting of the continental crust has been inferred. For the metapelites of the Usagaran Belt, peak metamorphic conditions of 1.8-2.0 GPa and 750-800°C have been deduced by Möller (1995). However, the composition of exsolved ternary feldspars indicate peak temperatures of at least 900°C.

The polymineralic inclusions in garnet are partly euhedral and have variable assemblages. However, two main types can be distinguished:

I. Quartz+plagioclase+biotite ±kyanite ±carbonates (apatite, zircon, monazite, rutile)

II. Dolomite+quartz+kyanite

In Type I inclusions the volume percentage of carbonate is <10% and carbonate cannot be detected in all inclusions. In Type II inclusions carbonate is a main constituent and reaches about 30 vol%. To get an idea of the melt composition, preliminary piston cylinder experiments were aimed to rehomogenize the polymineralic inclusions. At a pressure of 1.5 GPa, temperatures have been varied from 750°, 850° to 900°C. Backscatter images show that at 900°C some of the Type I inclusions homogenized nearly completely with an associated bubble while others were partly molten and glass is found in between rounded quartz, plagioclase and biotite relics. EMS analyses of glass give a peraluminous, siliceous melt composition. The remelting experiments confirm the silicate-rich inclusions as former melt inclusion. Type II inclusions, however, show numerous porosities but no indication of rehomogenization at 900°C and 1.5 GPa. These inclusions may have been formed by reaction of a carbonaceous fluid or melt with the garnet host. Associated with the polymineralic inclusions in garnet are pure $CO_2$ fluid inclusions with Ca/Mg-carbonate daughter minerals enclosed in the fluid inclusions (Herms, 2002). This points to the presence of Ca and Mg components in the original fluid.

**References:**

Herms, P. (2002) Eur. J. Mineral 14, 361-373.

Möller A. et al. (1995) Geology 23, 1067-1070.

Möller, A. (1995) unpublished PhD thesis, University of Kiel, 281p.

Talk

## From orogen to atomprobe – Micro-geochemical investigations of disequilibrium textures to reveal geodynamic processes

**Matthias Konrad-Schmolke**

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Many disciplines in geosciences face the complexity that mechanisms operating at the nano-scale control large-scale processes. Ever since Sorby the geoscientists are aware of this problem, hence the advancement of geoscientific research was to a large degree coupled to technical developments that pushed analytical possibilities to ever smaller scales. Nowadays, we know that observations down to the atomic scale are necessary to understand specific rock forming processes that might control even the formation of mountain belts. Especially compositional disequilibrium textures, such as partially overprinted mineral grains or growth zonations, are more and more in the focus of micro-geochemical and micro-textural investigations. Together with large-scale observations in Nature and numerical simulations disequilibrium textures are the key for the quantification of geodynamic processes. In this contribution I will focus on three examples of micro-geochemical investigations in four different minerals that yield unique information about geodynamic processes. In all examples it is evident that only the combination of careful sample selection together with latest analytical methods and numerical simulations represents the most promising approach to decipher geodynamic processes. In the first example I will demonstrate how we can evaluate inasmuch trace element growth zonations in garnet reflect the host rock's reaction path, mineral equilibria or element transport kinetics. In the second example I will focus on mica, which is one of the most important metamorphic rock forming minerals with respect to geochronology. I will show how we can extract valuable chronological information from partially overprinted grains and link this information to the rock's metamorphic history. In the last example I will show nano-scale evidence for a new dissolution-reprecipitation mechanism in pyroxenes and amphiboles with implications for metamorphic reaction rates.

Talk

## In-situ U-Th-Pb dating of metamorphic garnet, staurolite and accessory phases

**Leo Millonig[1], Axel Gerdes[1], Richard Albert[1], J.J. Ague[2], Dov Avigad[3]**

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The P-T-*t* evolution of metamorphic rocks is commonly inferred from tying P-T data obtained from major phases to U-Pb geochronological data obtained from accessory phases. This metamorphic evolution may be more adequately described, if geochronological data obtained from, *e.g.*, garnet and staurolite by in-situ techniques could also be considered. Opposed to monazite and zircon, however, metamorphic garnet and staurolite generally have very low U contents (< 0.3 ppm) and contain abundant inclusions, which renders the extraction of meaningful U-Pb ages difficult.

In this study we apply LA-ICP-MS U-Th-Pb dating of monazite, xenotime, zircon, garnet and staurolite to samples from the Straits Schist, SW Connecticut, a Silurian-Devonian sediment that experienced amphibolite facies metamorphism at ~390-380 Ma [1, 2].

Our approach includes determining the trace element composition of pure garnet and staurolite, characterization and dating of accessory phases in the matrix and included in garnet and staurolite, and dating of inclusion-poor and inclusion-rich garnet and staurolite domains. Our preliminary results indicate that monazite growth occurred at multiple times between ~390-360 Ma, dependent on the textural position. For example, monazite included in tourmaline yields ~385 Ma, whereas matrix monazite may be as young as ~360 Ma. Zircon in the matrix and included in garnet and staurolite is mainly inherited and U-Pb ages range between >1000 and ~450 Ma. Garnet and staurolite in the investigated samples rarely contains monazite, but frequently contains zircon. U-Pb dating of various garnet grains suggests that the main period of garnet growth occurred at ≥394 Ma.

These results, except for the ~360 Ma monazite ages, are in general agreement with published U-Pb monazite ages of ~379-384 Ma, garnet ages of ~418-383 Ma, and staurolite ages of ~400-394 Ma, obtained by solution techniques [1].

[1] Lanzirotti and Hanson (1995) Geochim. Cosmochim. Acta **59**, 2513–2526. [2] Tracy (2002) GSA NE Section - **37th** Ann. Meeting, Session 18.

Talk

## In-situ LA-ICP-MS U-Th-Pb monazite dating of metapelites from Namche Barwa area, Eastern Tibet, China

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The Namche Barwa Complex (NBC) in Eastern Tibet is an actively deforming metamorphic complex with an ambiguous tectonic and metamorphic history [1]. In order to better constrain the timing of metamorphism in this area, we apply in-situ LA-ICP-MS U-Th-Pb dating of monazite to metapelitic samples.

The result of the U-Th-Pb dating shows three distinct age groups : ~18-21 Ma, ~7.5-13 Ma and ~3.5-5.5 Ma. Except for one "sponge-like" grain, only these monazites in or related to garnet yielded the oldest group of ages. Monazite grains in matrix yielded the younger ages (<13 Ma) and no obvious evidence shows they can be classified according to the distinct crystal textures.

At present, our results suggest that garnet growth associated with prograde metamorphic stage took place between ~21 to 18 Ma, which is younger than previous proposed peak metamorphism at ~40 Ma or ~25 to 20 Ma [2-4]. The younger ages (<13 Ma) are similar to those reported by [1] and probably related to local anatexis and rapid denudation. Whether our newly obtained ages represent distinct metamorphic episodes or one metamorphic event with continuous mineral reactions is not conclusive and warrants further work, for example, the reconstruction of the *P-T-t* path for these metapelites using conventional geothermobarometry and thermodynamic modelling.

[1] Booth, et al. (2009) *Geol. Soc. Am. Bull.* 121(3–4), 385–407. [2] Ding, et al. (2001) *Earth Planet. Sci. Lett.* 192, 423–438 [3] Su, et al. (2012) *Int. J. Earth Sci.* 101, 239–252. [4] Xu, et al. (2010). *Tectonophysics.* 485, 231–244.

Poster

## Evolution of Saxothuringian medium-grade metapelites from the Vogtland combining geothermobarometry and monazite in-situ dating

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In the Elstergebirge of the Vogtland, metapelites of the Saxothuringian zone occur containing garnet and/or chloritoid. These rocks were mapped but poorly studied for their metamorphic evolution so far probably because they crop out in the border zone of Germany and the Czech Republic. We sampled over the last years numerous micaschists around the town of Asch/Aš and report here new results on two samples (coordinates of 14AS13: 50°14.39'N, 12°12.36'E; 14AS18: 50°14.78'N, 12°13.54'E). As presented in recent papers of the petrology group in Stuttgart, we combined geothermobarometry, based on pseudosection modeling with PERPLE_X, with monazite in-situ dating using an electron microprobe.

The samples are rich in quartz and potassic white-mica (KWM) and additionally contain biotite, chlorite, garnet, plagioclase and ilmenite. Accessories are apatite, monazite, zircon, and rutile. Garnet forms up to 3 mm-sized euhedral porphyroblasts in sample 14AS13. These blasts are chemically zoned with $Alm_{69}Grs_{19}Pyp_{3}Sps_{9}$ in the inner-most core and $Alm_{84}Grs_{6.5}Pyr_{6}Sps_{3.5}$ in the outer-most rim. Garnet in sample 14AS18 is characterized by up to 0.6 mm-sized, inclusion-rich grains with resorbed rims. Its composition varies from $Alm_{64}Grs_{24}Prp_{4}Sps_{8}$ in the inner-most core to $Alm_{71}Grs_{16}Prp_{6}Sps_{7}$ in the outer-most rim. KWM shows a compositional variability with Si (pfu) contents between 3.15 and 3.37 in 14AS13 and 3.09 and 3.16 in 14AS18. The higher Si contents occur in cores of grains. For both samples early pressure-temperature (P-T) conditions of 12-13 kbar and 520 °C were derived. Late P-T conditions were 7 kbar and 560 °C at which biotite and plagioclase formed at the expense of KWM, garnet, paragonite and chloritoid. The latter two phases were completely consumed.

EMP analyses of monazite revealed ages between 262 and 413 Ma with the most prominent (side) maxima at 293 ± 2.2 (2σ), 308.5 ± 1.9, 325.2 ± 1.4 and 340.3 ± 2.2 Ma. Ages younger than about 330 Ma were related to pulses of post-kinematic granite intrusions. Rare ages older than 350 Ma were assigned to the high-pressure (>10 kbar) event that was more obvious in a studied garnet-bearing micaschist occurring a few kilometers southwest of Asch (Rahimi and Massonne, in press). This event in the Late Devonian is due to the collision of Eastern Avalonia (as part of Laurussia) with northern Gondwana (or a peri-Gondwanan terrane). The age peak at 340 Ma represents a second metamorphic overprint at medium pressures (7 kbar) explained by further continental collision probably south of the Moldanubian Zone.

Poster

## The pre-Alpine polymetamorphic basement of the Southern Alps: A new petro-geochronological data set from the Dervio-Olgiasca Zone

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Situated north of Como lake and south of the Insubric Line, the Dervio-Olgiasca Zone (DOZ, Bertotti et al., 1999; Spalla et al., 2000) belongs to the Southern Alps and provides ideal conditions to properly investigate the pre-Alpine crustal evolution due to the absence of Alpine metamorphism (Crespi et al, 1982).

The classical Variscan metamorphic paragenesis (Grt-St-Wm-Bt±Ky) has been partially recrystallised (Bt-Wm-Sil-Grt) during a Late Permian to Middle Triassic LP-HT thermal event. A new set of petro-geochronological data with Lu/Hf on garnet and U-Pb and Th/Pb on monazite has been produced on pegmatite and micaschist. These datable minerals texturally correlated with the tectono-metamorphic evolution of the schist allow to reconstruct the tectono-thermal state of the Adriatic middle crust.

Our study reveals the occurrence of a Late Permian to Triassic thermal event (LP-HT) which induced a basement recrystallization only at the deepest exposed structural level of the South Alpine crust. Afterwards, because of the cooling of the crust, greenschist-facies overprint occurs close to lithospheric-scale extensional fault such as the well-known Lugano - Val Grande Fault (LVGF). It overprints the Variscan paragenesis at shallow crustal levels (upper crust) and has a large influence on the pre-alpine structure of the basement.

Our results reveal that the Adriatic crust experienced local, intense metamorphic events not related to Variscan or Alpine convergences, but to rifting processes related to the opening of the Alpine Tethys ocean.

Bertotti G., Seward D., Wijbrans J., ter Voorde M. & Hurford A.J. 1999. Crustal thermal regime prior to, during, and after rifting: A geochronological and modeling study of the Mesozoic South Alpine rifted margin. Tectonics, 18, 185-200.

Crespi R., Liborio G. & Mottana A. 1982. On a widespread occurrence of stilpnomelane to the South of the Insubric line, Central Alps, Italy. Neues Jahrbuch für Mineralogie-Monatshefte, 6, 265-271.

Spalla M.I., Siletto G.B., di Paola S. & Gosso G. 2000. The role of structural and metamorphic memory in the distinction of tectono-metamorphic units: the basement of the Como lake in the Southern Alps. J. Geodynam., 30, 191-204.

Talk

## Petrochronology of kinzigites in the Variscan Saxonian Granulite Massif by electron microprobe analysis and electron microscopy

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The Saxothuringian Zone in the eastern part of the Variscan orogen is composed of autochthonous and allochthonous domains. The dating of metamorphic events in the Saxonian Granulite Massiv (SGM), and the Münchberg and Frankenberg Massivs, and Erzgebirge

Nappe Units is critical for resolving the geodynamic evolution during the Variscan orogeny. In-situ chemical Th-U-Pb monazite dating by electron microprobe has demonstrated its potential to resolve polyphase metamorphism. Monazite is abundant in cordierite-sillimanite-garnet-gneisses (kinzigites), but rare in the quartz-feldspatic kyanite-garnet-gneisses of the Saxonian Granulite Massiv. Monazite at 10-200 µm in foliated matrix, enclosed in garnets has been detected by automated SEM-MLA (Mineral Liberation Analyser) methods in thin sections. An electron microprobe (EMP) Th-U-Pb monazite dating routine, was performed with a JEOL-8530F, producing 100 - 200 single analyses per sample. Energy dispersive x-ray mapping GXMAP of automated SEM-MLA was used for semiquantitative identification of garnet zonation patterns [2]. Quantitative chemical compositions of garnet and related plagioclase, biotite and cordierite were then measured by EMP for geothermobarometric estimates by cation exchange and net transfer reactions.

Garnets in the kinzigites from Mohsdorf in the central part and the SE margin of the SGM display Ca- and Mn-rich cores, and Mg-rich rims of prograde metamorphism. The *P-T* paths started at ~550 °C/6 kbar and reached maximum pressures at 700 °C/8 kbar. Maximum temperatures were approached at 750-800 °C/4 kbar. A significant decrease of temperatures at low pressures was recorded by decreasing Mg contents in the garnet rims. $ThO_2$*-PbO isochrones of monazites enclosed in the kinzigite garnets range between 340±8 to 330±4 Ma and appear to be slightly older as the matrix monazites (331±5 to 317±5 Ma). As P-T conditions from garnet-bearing equilibria match the stability field of monazite, this may bracket the period of garnet crystallisation. In garnet-free granulites and gneisses, considerably older metamorphic monazite with isochrone ages at around 358±8 Ma, and monazite populations at 407-440 Ma have been detected. The post-340 Ma monazite populations match zircon and Ar-Ar data as summarised in [2]. Also the 335±2 Ma monazites from a discordant granite match earlier results from such rocks.

**References**

[1] Schulz, B. (2017) Polymetamorphism in garnet micaschists of the Saualpe Eclogite Unit (Eastern Alps, Austria), resolved by automated SEM methods and EMP-Th-U-Pb monazite dating. J. Metam. Geol., *35*:141-163.

[2] Franke, W., Stein, E. (2000) Exhumation of high-grade rocks in the Saxo-Thuringian Belt: geological constraints and geodynamic concepts. Geol. Soc. London Spec. Publ., 179, 337-354.

**Talk**

## Paleopiezometry: A powerful tool for stress measurements in the Earth’s crust and mantle

**Michael Stipp**

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Tectonic stress controls the deformation of the Earth’s crust and mantle ranging from seismic rupture on discrete faults to plastic flow processes in wide mylonitic shear zones. Due to the restricted access towards greater depth direct stress measurements are largely impossible. Our knowledge on the stress state of the lithosphere is therefore mostly based on paleostress estimates in exhumed shear zones. These indirect stress measurements are carried out using microstructural indicators (paleopiezometers) similar to the concept of thermo- and barometry in petrological studies. The most reliable and widely used paleopiezometer is the dynamically recrystallized grain size resulting from dislocation creep, a dominant plastic flow mechanism within the intermediate and lower continental crust and the upper mantle.

Piezometers are experimentally calibrated for the most important rock forming minerals, e.g., olivine, pyroxene, plagioclase, quartz, calcite, but there are also a number of theoretical piezometer models, which have been proposed. In these models, the recrystallized grain size has been suggested to be not only a function of stress, but also of temperature, strain, and other parameters. While most of the piezometer models predict a temperature dependence via an activation energy term, neither an increase nor a decrease in recrystallized grain size with increasing temperature has reliably been shown by deformation experiments on different minerals. A strain rate dependence is not constrained by experimental data and also a waterdependence of the piezometer does not exist for quartz and there is contradicting experimental evidence for olivine. A recrystallized grain size compilation of quartz mylonites worldwide indicates that the recrystallized grain size development is significantly controlled by the different recrystallization mechanisms. The piezometer models should reflect this relationship, which is, however, not the case.

Recent developments improve the quantification of the microstructural indicators using the electron backscatter diffration technique (EBSD). High-angular resolution EBSD allows to measure subgrain misorientation and size in an accuracy close to that one of transmission electron microscopy and hence to calibrate corresponding piezometers. It has been shown by EBSD data that there are differences in the recrystallized grain size between general shear and axial shortening experiments when applying the standard conversion for stress. General shear samples display small, but significant variations in the recrystallized grain size depending on microstructural position, crystallographic orientation and shear strain within a single experiment. These and further new observations are important to better constrain the dependency of recrystallized grain size on stress and related piezometer models.

# 3b) The Eastern Mediterranean: A natural laboratory to study orogenic processes operating at different times and at different structural levels

**Poster**

## Fault slip analysis on Amorgos Island (Greece)

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Amorgos is the south-eastern outpost of the Cyclades Islands in the Aegean Sea, which forms part of the Neogene-Quaternary zone of crustal and lithospheric N-S upper plate extension northward of the Hellenic subduction zone and deep sea trench. Apart from subduction-related earthquakes further south, the south Aegean is affected by frequent earthquakes sourced in the upper plate. The twin earthquakes (Ms = 7.4 and 7.2) of 9 July 1956 were the largest events of this kind in the 20th Century, with epicentral locations SW of Amorgos related to a NE-SW oriented major rupture in the upper plate around the Amorgos-Santorini Graben System, followed by a strong tsunami. There have been questions in the literature regarding the seismic source and fault plane solutions, especially the contribution of a transcurrent component to co-seismic motion.

This prompted our investigation of brittle fault kinematics on Amorgos Island itself, that could be related to Neogene and active extensional and/or transcurrent deformation. Seismic slip often occurs on previously existing faults, and their orientations and kinematics may, thus, help shed light on the seismic source at depth.

From published mapping and our own observations a complex history of faulting can be derived. Early normal detachment faults and shear zones and yet older (rare) reverse faults, are overprinted by several sets of strike slip faults and younger normal faults. Strike slip faulting is dominantly dextral, with the majority of fault planes trending NE, and a secondary set trending SE. Normal fault population forms conjugate sets, with a NE-SW axis of intersection. Normal faults are especially frequent along the SE coast of the island, suggesting a clear spatial relationship with the 1956 rupture. Almost all normal faults can be fitted to one moment tensor solution that generally fits the published solutions for the 1956 Amorgos earthquake. Regarding long-term upper Neogene to Quaternary kinematics, dextrally transtensive fault slip is required to fit the regional pattern of extensional deformation in the Aegean, and this is apparently reflected by small-scale brittle faulting on Amorgos.

**Poster**

## Tectonic and metamorphic frameworks of the Eastern Mediterranean: a preliminary work

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Based on the experience of the making of the maps of Mesozoic to Tertiary metamorphism in the Alps “Metamorphic Structure of the Alps” (Oberhänsli, et al. 2004, Bousquet, et al. 2012a) and “Tectonic Framework of the Alps” (Schmid et al., 2004, Bousquet, et al. 2012b), where an interplay of data from structural geology and tectonics with metamorphism as well as age data and geophysical information was used to visualize the spacio-temporal geodynamic evolution of this complex orogenic system, we present a new tectonic frame for the continuation from the Alps to the Asia Minor. This map includes the Balkan, Aegean and Turkish realm in Asia Minor including the Carpathians, Dinarides, Rhodopes, Peloponnese, Aegean as well as Pontides and Taurides. The motivation for the compilation of this map is based on new metamorphic and age data especially for the Carpathians, Rhodopes, Aegean and Turkey. A tectonic map of the Carpatho-Dinaride realm that is consistent with a basic scheme of continental and oceanic realms and their structural relation as developed for the Alps was published by Schmid et al (2008): However, the east ward continuation across Asia Minor is missing. With this new general map, we try to solve the problem of the continuation of the different continental and oceanic units from the Balkan over the Peloponnese and Aegean into Turkey and further to Iran. Due to intense neotectonic effects and movements and the Miocene to Neogene basins and volcanics that cover major parts of Turkey this is still speculative. Several small continental units (Menderes, Kirsehir) of Pan African origin, carrying along old metamorphism, are amalgamated along several Tethyan oceanic units and cannot simply be correlated with the Balkan setting.

Oberhänsli, R., Bousquet, R., Engi, M., et al. (2004) Metamorphic structure of the Alps -1st Edition, *Commission for the Geological Map of the World (CCGM/CGMW)*, Paris,

**Bousquet R.**, Oberhänsli, R., Schmid, S. Met al. (2012a) Metamorphic framework of the Alps (1:1’000’000) 2d Edition *(CCGM/CGMW)*, Paris.

Bousquet, R., Schmid, S. M., Zeilinger, G., et al. (2012b) Tectonic Framework of the Alps (1:1’000’000), *(CCGM/CGMW)*, Paris

**Schmid, S. M.**, Fügenschuh, B., Kissling, E. and Schuster, R. (2004). Tectonic map and overall architecture of the Alpine orogen. Eclogae geologicae Helvetiae 97: 93-117.

Schmid, S. M, Bernoulli, D., Fügenschuh, B et al. (2008) The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units (2008) Swiss J. Geosci. 101: 139.

**Poster**

## Structural evolution of the Makrotantalo nappe (Cyclades, Greece)

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New detailed geological and structural mapping from northern Andros combined with microstructural and amphibole chemistry mineral-analyses provide new insights on the deformation history of the Makrotantalo nappe. The Makrotantalo nappe is tectonically emplaced over the North Cycladic nappe, but its tectonometamorphic evolution remains enigmatic. It is considered either as a part of the upper plate of the Alpine subduction system or as a part of the Cycladic Blueschists. The major reason of this controversy is that the contact between the Makrotantalo and the underlying North Cyclades nappe is not clear-cut. All earlier studies are based on the first and unique map for the area in which the contact is very roughly mapped.

Our analyses exhibit that both nappes underwent two main phases of ductile deformation. The early deformation phase is associated with the emplacement of the Makrotantalo over the North Cycladic nappe in blueschist-facies conditions. This emplacement was likely achieved by E-directed thrusting. The subsequent exhumation-related deformation is mainly represented by a gently (W)NW-dipping foliation, which is axial planar to outcrop- to map-scale NE-trending folds. The early nappe contact between the Makrotantalo and the North Cycladic nappe has intensely overprinted by this folding event. We also mapped a series of NE-directed ductile shear zones, which cut out the short limb of map-scale folds or are developed parallel to the long limb of such folds. These shear zones typically transpose the early nappe contact carrying the North Cycladic over the Makrotantalo nappe. Amphibole mineral-chemistry analyses showed that the NE-directed shearing commenced under blueschist- facies conditions and continued progressively at greenschist-facies conditions. Overall, we suggest that the Makrotantalo nappe is an integral part of the Cycladic Blueschists.

**Poster**

## In-situ U-Pb ages of multiple generations of calcite veins related to the Ivriz Detachment, Central Anatolia

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Absolute in-situ dating of tectonic structures and related overprinting fabrics is vital for comprehending the relative timescales and rates of deformation at shallow crustal levels. In the Mediterranean region, such tectonic fabrics are frequently contained in Mesozoic carbonates, which are challenging to date. U-Pb dating of low U-concentration rocks (<10 ppm) has only recently been used for dating diagenesis and deformation structures contained in calcite fibers. The Ivriz Detachment, central Anatolia bounds the Taurides carbonate platform, which in places has undergone HP-metamorphism. This structure played a key role in the exhumation of HP-metamorphic rocks from greenschist-facies conditions by normal-sense structural attenuation of the overriding plate. Related calc-mylonites and calc-schists show semi-ductile to brittle deformation with a normal sense of shear. In this study, we targeted structural domains of several generations of overprinting structures marked by calcite fibers in eleven samples and report absolute ages for diagenetic and subsequent deformation events. The oldest obtained U-Pb ages from the carbonates reflect Mesozoic diagenesis as part of the Tauride platform. A latest Cretaceous-Paleocene age is evident in two samples and overlaps with retrograde phengite $^{40}Ar/^{39}Ar$ growth ages of 67–62 Ma assigned to the onset of exhumation of the Afyon HP-rocks [(1)]. A subsequent extensional event is recorded in six samples ranging from 60-56 Ma, consistent with U-Pb crystallization ages from syn-kinematic intrusions of the same age and the main phase of activity of the Ivriz Detachment [(2)]. Two younger events in Mid to Late Eocene time may be assigned to regional exhumation. The younger of these two events is associated with purely brittle deformation fabrics and may represent final unroofing of the Taurides in the footwall of the Ivriz Detachment. Our results show that in-situ U-Pb dating of calcite fabrics can be successfully used to constrain absolute ages of diagenesis and deformation when put into context with relative constraints coming from field relations and microstructural techniques.

1. Pourteau, A. *et al.* Neotethys closure history of Anatolia: insights from 40 Ar- 39 Ar geochronology and P-T estimation in high-pressure metasedimentary rocks. *J. Metamorph. Geol.* **31,** 585–606 (2013).

2. Gürer, D. *et al.* A long-lived Late Cretaceous-Early Eocene extensional province in Anatolia? Structural evidence from the Ivriz Detachment, southern central Turkey. *Earth Planet. Sci. Lett.* **481,** 111–124 (2018).

**Talk**

## A NEW PETROGENETIC MODEL FOR LATE NEOPROTEROZOIC GRANITOIDS AND GABBROES IN THE MENDERES MASSIF, WESTERN TURKEY: IMPLICATIONS FOR LATE-STAGE CADOMIAN MAGMATISM IN THE PAN-AFRICAN MEGA-CYCLE

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Cadomian-origin Late Neoproterozoic magmatism in the peri-Gondwanan part of Turkish terranes is best observed in the Tauride-Anatolide Platform (TAP), the South Anatolian Autochthone Belt in the southern and the Istanbul-Zonguldak Terrane and Strandja Massif in the northern part of the country. These were separated from each other by the openings of the Zagros and Izmir-Ankara-Erzincan Neotethyan oceanic seaways during the Late Palaeozoic-Early Mesozoic. Zircon crystallization ages previously determined by LA-ICP-MS in the TAP of the Menderes Massif (MM) yielded ~591 to 582 Ma for arc-related meta-tonalites/meta-granodiorites that are frequently cut by ~563 to 558 Ma back-arc related meta-gabbros and followed by late to post-collisional ~554 to 545 Ma meta-granites. Andean type affinity of the meta-tonalites/meta-granitoids in the MM is expressed by their pronounced enrichment of LREE over MREE and HREE, with ($(La/Yb)_N$- 4.75 to 12.34, $(La/Sm)_N$- 3.05 to 6.17, $(Gd/Yb)_N$- 1.0 to 1.35 and $(Eu/Eu)_N$- 0.54 to 0.85). Th, Nb, Zr, Y and Ti contents of the meta-gabbros observed within the basement rocks are in the range of 0.2 to 11.7 ppm, 3.6 to 18.4 ppm, 74.2 to 234.3 ppm, 17.8 to 37.2 ppm and 4676 to 14508 ppm, respectively. They show continental back-arc geochemical affinity, combined with low Ti/Zr (23.03 to 66.76) and high Zr/Yb (40.65 to 62.44) ratios with enriched Nb (mean 11.4 ppm), Th (4.4 ppm) and Zr (167 ppm) contents. This implies that they might have been produced by melting of a depleted mantle source that assimilated crustal materials. The youngest meta-granitic rocks in the MM (~545 to 554 Ma) have high HFSE and HREE-enriched multi-elemental patterns with negative $\varepsilon Nd_{(t)}$(-4.63 to -0.54) values that indicate mafic sources with limited mixing of continental crustal material in their genesis. In the basement rocks of the MM, Andean-type arc-related igneous activity (~592-582 Ma) was followed by lithospheric thinning and resulted in genesis of the meta-gabbroic dikes (~563 to 558 Ma) during the initial stage of back-arc basin formation, followed by late- to post-collisional granitoid intrusion (~554 to 545 Ma) during the mature stage of back-arc extension behind the Cadomian arc. This was concomitant with southward subduction of the Proto-Tethys Ocean along the northern margin of Gondwana. This scenario can be correlated well with geodynamic models of Late Neoproterozoic-Early Cambrian rocks in other peri-Gondwanan terranes in W and E Europe, N Africa and S Asia, which were affected by the Cadomian orogeny of the last phase of the Pan-African mega-cycle.

Poster

## GEOCHEMICAL AND ISOTOPIC DATA OF META-GABROIC DIKES IN ALAŞEHİR AREA IN THE MENDERES MASSIF, WESTERN TURKEY: EVIDENCE FOR THE EARLY CAMBRIAN BACK-ARC RIFTING?

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Stratigraphic feature of undated garnet-bearing meta-gabbroic dikes cross-cutting basement rocks of meta-pelitic successions in the Alaşehir areas (Central Menderes Massif - CMM) are still in debate and are distinct from the eclogitic meta-gabbroic dikes, garnet amphibolites and biotite rich meta-gabbroic dikes cross-cutting Neoproterozoic basement rocks (meta-tonalites/meta-granodiorites and meta-granites) that crop out in the Birgi, Tire and Çine areas of the CMM. The garnet-bearing meta-gabbro dikes in the Alaşehir areas have low Nb (0.6 to 4.9 ppm), low Th (0.2 to 0.5 ppm), low Zr (10.1 to 54.6 ppm), low to moderate Y (8.4 to 15.1 ppm), Ti (2518 t 6175 ppm), Zr/Yb (13.33 to 41.31 ), Ti/Zr (57.05 to 346.86), Y/Zr (0.23 to 0.98) ratios. They are highly depleted in LREE and display flat patterns in MREE and HREE compared to the eclogitic meta-gabbroic dikes, garnet amphibolites, biotite rich meta-gabbroic dikes of the Late Neoproterozoic basement rocks. Nb, Zr, Ti contents with Nd/Sm and La/Yb ratios compared to La/Yb and Eu/Eu* indicate distinct enrichment of the garnet-bearing meta-gabbroic dikes (Alaşehir areas) relative to the eclogitic meta-gabbroic dikes, garnet amphibolites and biotite rich gabbroic dikes (Birgi, Tire and Çine areas). The low Nb, low Th, low Zr contents, and high Ti/Zr and low Zr/Yb ratios in the garnet-bearing meta-gabbroic dikes (Akşehir areas) compared to the eclogitic meta-gabbroic dikes, biotite rich meta-gabbroic dikes indicates that they may have been derived from melting of mafic lower crustal sources. Variable $_{\varepsilon}Nd_{(540)}$ (-2.9 to +1.9) and $^{147}Sm/^{144}Nd$ ratios (0.1320 to 0.2277) of the garnet-bearing meta-gabbroic dikes in Alaşehir areas indicate extensive mixing of a mafic lower crustal source with depleted mantle during their formation. Apparent crustal residence Nd model ages ($T_{DM}$) determined using the two-stage model of Liew and Hofmann (1988) range from 1.08 - 1.47 Ga, also indicating mixing of older sources with depleted mantle. We suggest that Andean-type subduction was followed by lithospheric thinning of the continental crust, resulting in an initial stage of back-arc basin formation in the peri-Gondwanan crust during the Late Neoproterozoic. The biotite-rich meta-gabbroic dikes may have been generated during the initial stage of this rifting, whereas garnet-bearing meta-gabbroic dikes (Alaşehir areas) may have been generated later during the mature stage of continental rifting in the Early Cambrian. Similar tectonic scenarios have been suggested for other peri-Gondwanan terranes in Europe, the Middle East, and eastern Asia.

Talk

## Dating extensional deformation within an accretionary prism by means of Ar/Ar-in-situ geochronology

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Ar/Ar-in-situ geochronology provides a powerful tool to study the inter- and intra-granular age variations of minerals while maintaining textural control of the sample. In order to date exhumation/extensional deformation in the Internal Dinarides, we selected samples from two metamorphic core complexes located at the distal Adriatic passive margin and within the Sava Zone. The Sava Zone represents a suturing accretionary prism separating lower-plate Adria-derived thrust sheets of the Internal Dinarides from European units in the upper-plate position. In Oligo-Miocene times, the Sava Zone underwent substantial post-collisional extension, triggered by the opening of the

Pannonian Basin in response to the NE-directed rollback-motion of the Carpathian slab.

We sampled the metamorphic core complexes (MCC) of Motajica, situated in the Sava Zone in northern Bosnia and Hercegovina and Cer MCC in central western Serbia, situated within the Jadar-Kopaonik composite nappe, that represents the most distal Adriatic thrust sheet. Exhumation of a central granitoid pluton along with a framework of amphibolite-grade rocks composed of paragneisses and mica schists took place within a zone of ductile deformation (Motajica detachment) at Motajica MCC, generally exhibiting top-WNW transport during upper greenschist-facies conditions.

Similar to Motajica MCC, Cer MCC is composed of a multiphase pluton surrounded by mica schists of up to amphibolite facies grade. Analyzed samples from Cer MCC represent deformed pegmatite-veins within a suite of mica schists metamorphosed under upper greenschist- to lower amphibolite facies conditions with temperatures obtained from RSCM (Raman Spectroscopy on Carbonaceous Matter) reaching from 550-600°C.

The focus during Ar/Ar-in-situ geochronology lies on precise dating of pre-, syn-, and post-kinematic mica grains, which were previously deformed during exhumation of the core complexes along former Maastrichtian thrusts, later reactivated as low-angle detachments in Oligo-Miocene times.

Here we attempt to differentiate between these two events. Our preliminary results might improve timing constraints on the extensional deformation, related to the opening of the Pannonian Basin, which exhumed not only part of the accretionary prism of the Sava Zone, but also affected the most distal Adriatic basement.

**Poster**

## Evolution of the Palaeotethys in the Eastern Mediterranean: Age, provenance and tectonic setting of the Upper Palaeozoic Konya Complex and its Mesozoic cover sequence (south-central Turkey)

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The Eastern Mediterranean region experienced intense geodynamic reorganization during the Palaeozoic and Mesozoic era due to the opening and closure of the Palaeo- and Neotethyan oceans. Important exposures of Palaeotethys-related sedimentary successions are known, for example, from Chios (eastern Greece), Karaburun (western Turkey), and the Konya Complex (south-central Turkey). They are considered as key areas for understanding the closure history of Palaeotethys. The Konya Complex, located 30 km NW of Konya city, is the focus in this study. It is part of the Afyon Zone on the northern margin of the Anatolide–Tauride Block. The Anatolide–Tauride Block is subdivided into an unmetamorphosed Gondwana-derived southern part referred to as Taurides and the northerly Anatolides representing the northern passive margin of the Palaeotethys in Palaeozoic time. Northward subduction of the Palaeotethys during the Carboniferous led to formation of magmatic arc/fore-arc complexes and to amalgamation of both blocks in latest Triassic time when the Palaeotethys (supposedly) finally closed. In an alternative view, the Anatolide–Tauride Block is interpreted as part of the passive northern margin of Gondwana that switched to an active margin with induced back-arc rifting during the Carboniferous. Different palaeotectonic models and implications for the evolution of the Palaeotethys are strongly debated in the literature. Essential provenance data for verification are still scarce. In this regard, the investigation of Palaeozoic and Mesozoic ocean-related sedimentary successions is of special importance. The Konya Complex is generally thought to comprise a Palaeozoic carbonate platform that is overlain by siliciclastic sediments with olistoliths and volcanic-sedimentary rocks. Our main objective is to provide an extensive dataset for the siliciclastic rocks of the Konya Complex to shed light on their age, composition, and origin. Here, we present results from a multi-parameter provenance analysis utilising thin-section petrography, bulk-rock geochemistry, single-grain geochemistry, and U–Pb LA-ICP-MS zircon dating. Detrital zircon ages – in particular Silurian–Devonian and Ordovician–Silurian populations – record major sediment supply from units of the southern Eurasian margin but minor input from North Gondwana as well. In contrast to sediments from Chios and Karaburun, detrital garnet and Cr-spinel are virtually absent in the studied rocks from the Konya Complex. Tectonometamorphic and structural studies will contribute for reconstructing the palaeoposition of these rocks within the Tethyan realm.

**Poster**

## The Uppermost Unit south of the Dikti Mountains, eastern Crete (Greece): constraints on the tectonometamorphic evolution of the Internal Hellenides

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Records of Alpine orogenic imprints in the Internal Hellenides can be studied in the Uppermost Unit of Crete and on several Cycladic islands. The Uppermost Unit of the Cretan nappe pile escaped Oligocene to Miocene subduction as well as related deformation and metamorphism and is therefore a key in understanding the pre-Oligocene tectonometamorphic evolution of the Internal Hellenides in the southern Aegean.

We present a new geological map and new structural, petrographic and geochronological data obtained from rocks of the Uppermost Unit exposed south of the Dikti Mountains in eastern Crete. The Uppermost Unit in this area can be subdivided into (from bottom to top): (1) prehnite pumpellyite facies pillow lavas with OIB signature, dolerite, pelagic carbonates and turbidites (Arvi Unit); (2) greenschist facies epidote-amphibole schists (Theodorii Greenschist); and (3) amphibolite facies orthoamphibolite, metasedimentary rocks and serpentinite (Asterousia Crystalline Complex; ACC).

The ACC-type rocks bear evidence for polyphase deformation and metamorphism. $D_1$ is preserved as internal foliation in garnet porphyroblasts, while amphibolite facies $D_2$ top-to-the SE shearing is related to the main pervasive foliation. After post-$D_2$ exhumation, parts of the ACC-type rocks were affected by metamorphism in the contact aureole of a shallowly intruded (< 10 km), non-exposed pluton. LA-ICP-MS U-Pb age dating on zircon from chiastolite hornfels yielded 74 ±2 Ma, which is compatible with published intrusion ages from other ACC-type (meta)granitoids and is interpreted as the age of intrusion and contact metamorphism. $D_3$ top-to-the SE shearing during the late phase of contact metamorphism caused reactivation of the $S_2$-foliation. Cross-mica with low Si content post-dates this shearing event. During the middle Palaeocene, the ACC was thrust on top of the Theodorii Greenschist under greenschist facies conditions. This thrusting event as well as subsequent thrusting of the greenschists and the ACC-type rocks on top of the Arvi Unit under prehnite-pumellyite facies conditions was still accommodated by top-to-the SE kinematics. The shear sense inferred compares well with that from exposures of comparable rocks in the area west of Melambes (central Crete) and on Anafi (Cyclades). All these events are related to the Eo-Alpine convergent movements and coeval slab roll-back along the northern margin of the Neotethys.

An origin of the I-type (meta)granitoids of the ACC from the Late Cretaceous Apuseni–Banat–Timok–Srednogorie-Strandja-Pontide magmatic arc is suggested.

Talk

## Late Miocene to Pliocene surface uplift of the Central Anatolian Plateau and its southern margin (Turkey)

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The geologic evolution of the Eastern Mediterranean region has been characterized by northward subduction of the Neo-Tethys Ocean since the Mesozoic, which led to accretion of a number of Africa-derived continental terranes, volcanic arcs, and carbonate platforms to the southern Eurasian margin. Present-day Turkey is an amalgam of the aforementioned elements, the last of which accreted during the Paleogene. As a result of ongoing Africa-Eurasia convergence, the formation of the Anatolian microplate and its westward escape into the Aegean domain has occurred since the Miocene.The modern Central Anatolian Plateau (CAP), with its subdued topography, is bordered to its south and north by steep mountain belts that roughly follow the trend of the formerly accreted terranes.A number of lines of evidence have continued to reveal the surface uplift history of Anatolia with increasing detail. Collectively, they indicate that the rise of the CAP and the southern Tauride margin have occurred during the last 11 Ma (i.e. since the late Miocene).

In this study, we document and quantify surface uplift of the southern CAP margin by providing an oxygen stable isotope-based paleoclimate and -elevation reconstruction of lacustrine carbonates from upper Oligocene to Pliocene continental basins within the plateau interior. Knowledge of the onset, duration and rate of orographic barrier formation is crucial for understanding the geodynamic drivers of surface uplift, as well as the impact of surface uplift on climatic conditions. The studied sections are firmly dated owing to a geochronological framework based on existing mammal, radiometric and paleomagnetic age constraints, as well as new $^{40}Ar/^{39}Ar$ and paleomagnetic data.

We interpret the gradual ~4 ‰ decrease of $\delta^{18}O$ values of lacustrine carbonate in the southern plateau interior between ~11 and 5 Ma to reflect the late Miocene development of an orographic barrier along the southern plateau margin. Estimated paleoelevations indicate that the orographic barrier had reached its present-day average elevation of ~2 km by 5 Ma. The timing of surface uplift and contraction in the forearc suggests that subduction beneath Anatolia and associated crustal shortening was the main driver of surface uplift along the southern plateau margin.

Talk

## New structural and finite strain data from the Asteroussia Crystalline Complex (ACC) near Lendas (Crete): constraints on the tectonometamorphic evolution of the Uppermost Unit

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The Alpine nappe stack of the Hellenides consists of a lower part, related to the External Hellenides, and an upper part (Uppermost Unit), attributed to the Internal Hellenides. The Asteroussia crystalline complex (ACC) is one of the nappes of the Uppermost Unit characterized by (1) Late Cretaceous high-grade metamorphism (Seidel et al., 1981), (2) Campanian (meta)granitoids, and (3) top-to the SE shearing (Martha et al., 2017; 2018).

We present revised mappings and new structural, finite strain and microfabric data obtained from ACC-type rocks (amphibolite, calc-silicate rock, marble, (meta)-granitoids)exposed near Lendas (Crete). These rocks have been thrust on top of very low-grade metamorphic rocks of the Arvi Unit, the latter forming the structurally deepest nappe of the Uppermost Unit. The thrust contact includes greenschists (retrograde amphibolite) which has been mapped for the first time in this area.

The subhorizontal foliation of the ACC-type rocks results from a shape preferred orientation of the constituent minerals (quartz, feldspar, biotite, etc.). The direction of mineral/stretching lineation varies from NNE-SSW to NNW-SSE with a main peak along the N-S direction. Coaxial deformation prevails.

The foliation is particularly accentuated by numerous foliation-parallel quartz veins, which are up to 10 cm in thickness.

These veins are affected by chocolate-tablet boudinage, which results from a longitudinal strain of 1.4 ±0.3 in N-S and 0.4 ±0.3 in E-W sections. The aspect ratio of the boudins (3.9 ±1.3 in N-S and 3.3 ±0.7 in E-W sections) and their shape are characteristic for viscous boudinage resulting from pinch-and-swell structures. Deformation microfabrics of quartz, such as undulatory extinction, serrated grain boundaries and subgrains, aligned parallel to the prism planes, indicate viscous deformation under greenschist-facies conditions (ca. 300 – 500 °C). The size of recrystallized quartz grains is 56 ± 15 µm indicating a paleodifferential stress of 47 (+ 13/-8) MPa.

Taking K-Ar ages of hornblende (ca. 73 Ma) and biotite (ca. 70 Ma) into account (Seidel et al., 1981), which reflect cooling below ca. 500 and ca. 300°C, respectively, the formation of the quartz veins and their greenschist facies boudinage is well constrained to the late Campanian. However, it should be emphasized that the strain obtained from the boudinage of the quartz veins a lower bound for the finite strain of the ACC-type rocks.

Seidel, E. et al., 1981. Contrib. Mineral. Petrol, 76, 351–361. Martha, S.O. et al., 2017. Gondwana Res., 48, 50-71.Martha, S.O. et al., 2018. Geol. Mag.; https://doi.org/10.1017/S0016756818000328

Poster

## Thermochronological constrains on the bivergent exhumation of the Menderes Massif (western Turkey) along the Gediz and Büyük Menderes detachments

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The Alpine contractional regime, which formed the Anatolide nappe stack in western Turkey, changed during the late Oligocene into a sustained regime of continental extension, leading to the exhumation of the Menderes Massif. The extension was accommodated by low-angle detachment faults and led to the formation of two E-W striking graben systems, which separate the central Menderes Massif from the northern and southern submassifs (Gessner et al. 2013). In the central Menderes Massif, the late Cenozoic exhumation was accommodated by the north-dipping Gediz detachment and the south-dipping Büyük Menderes detachment and led to the exhumation of the Bozdag and Aydın mountain ranges, respectively. Many of the previous structural and thermochronological studies focused on the evolution of the well exposed Gediz detachment and inferred a similar development for the Büyük Menderes detachment. The concurrent activity of both detachments since the middle Miocene is indicated by thermochronological data, which revealed two phases of increased footwall cooling in the middle Miocene and in the latest Miocene/Pliocene (Buscher et al. 2013; Wölfler et al. 2017). However, a comprehensive tectonic model on the exhumation of the Aydın range is impeded by the scarcity of field data from structures related to late Cenozoic extension and thermochronological data, which provide improved constraints on the timing and along-strike changes of the Büyük Menderes detachment. Our results from structural and geological mapping show that the Büyük Menderes detachment consists of two overlapping fault segments, and not a single continuous detachment fault. New zircon and apatite (U-Th)/He and fission track ages from the western parts of the Aydın and Bozdag ranges corroborate the middle and latest Miocene/Pliocene cooling events and document along-strike variations in the exhumation pattern of both detachments. Exhumation rates, which are deduced from 1D thermo-kinematic modeling, enable us to constrain the relative contribution of each detachment to the exhumation of the central Menderes Massif. The onset of faulting along the active high-angle normal faults of the Gediz and Büyük Menderes graben systems is documented by late Pliocene and early Quaternary apatite (U-Th)/He ages.

Talk

## The story of Tethys in the Eastern Mediterranean – Black Sea region

**Aral I. Okay**

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The geology of the Eastern Mediterranean and the Black Sea region is linked with the evolution of the Tethys ocean, which separated the Gondwana from Laurasia during the Late Paleozoic-Cenozoic. The separation of Tethys into different parts, and their relation to the various terranes in the region are controversial. Especially, there are many theories on the location of the Paleo-Tethys and its relation to the Neo-Tethys. In the Eastern Mediterranean there are two main Tethyan sutures; the Assyrian-Zagros suture in the south represents an ocean, which opened in the Triassic, separating the Anatolide-Tauride Block from the Arabia, and partly closed in the Miocene; the Levant Basin in the Eastern Mediterranean is a relic of this ocean. The İzmir-Ankara-Sevan-Akera suture in the north has a longer and more complicated story.

Best evidence for the existence and demise of a former ocean is provided by its magmatic arcs and subduction-accretion complexes, both of which have high preservation potential. Triassic subduction-accretion complexes, known as the Karakaya Complex, are widespread in the Pontides and extend to the Caucasus and Crimea. The presence of Devonian, Carboniferous and Permian radiolarian cherts, Permian ophiolite fragments in the Karakaya Complex indicate the existence of a Late Paleozoic ocean south of the Pontides; Triassic oceanic eclogites in the Karakaya Complex show that this ocean was subducting north under the Laurasia during the Late Triassic. Detrital zircon data have recently shown the existence of a Triassic magmatic arc north of the Black Sea, now buried under young cover.

Data for the post-Triassic evolution of the Tethys ocean include Jurassic and Upper Cretaceous magmatic arcs, and Jurassic and Cretaceous subduction-accretion complexes with Lower Cretaceous eclogites in the Central Pontides. The Cretaceous subduction-accretion complexes contain Middle-Upper Triassic, Jurassic and Cretaceous radiolarian cherts associated with basalts indicating subduction of a Mesozoic Tethys ocean. Several studies have invoked a Cimmerian continent between the Paleo- and Neo-Tethys. However, the imbrication of the Jurassic and Cretaceous subduction-accretion complexes with the Karakaya Complex along the İzmir-Ankara suture leaves no room for a Cimmerian continent.

The view, which emerges from the data collected over the last 20 years is a wide Late Paleozoic-Mesozoic Tethys ocean subducting north under the Laurasia. The subduction is interrupted by collision of intra-oceanic edifices, such as oceanic plateaus, to the Laurasian margin, which grew southward through accretion. The İzmir-Ankara-Sevan-Akera suture represents the trace of a long-lived Late Paleozoic to Mesozoic Tethys ocean.

**Talk**

## Mediterranean Tectonics Unique to Its Salinity Crisis

**William B F Ryan**

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The unusual circumstance of the Mediterranean acquiring basins full of concentrated brine with a density exceeding 1.3 g/cm$^3$ followed by near-complete desiccation had unique consequences on volcanism, flexure from loading/unloading, critical taper of accretionary prisms, instability of sediment on slopes, and deformation within salt bodies themselves. For many the Messinian Salinity Crises began 5.97 ma with the first gypsum deposited in marginal regions. However, examination of the preceding Tripoli Formation shows a rise of salinity beginning 300 ka earlier with the eventual demise of marine faunal and flora well ahead of the first evaporite precipitates. Increasing density of the sea water induced the escape of lighter porewaters as observed in preserved vent communities, diagenetic products of methane escape, and the onset of mass-wasting from continental margins. Accumulation of halite in the basin depocenters began at nearly the same time as gypsum on the margins. The early halite layers contain evidence of clastic input as seen in seismic reflection profiles. Fan-like bodies appeared in the Herodotus Basin of the eastern Mediterranean within the halite as the Nile margin began to be dismembered. With increasing water density, the taper of the Calabrian and Mediterranean Ridge accretionary wedges steepened and its outward advance stopped as evidenced by the broad width of the salt deposit along the perimeters. The weight of brine and accumulating thick salt added a load to the lithosphere causing subsidence in the basins and peripheral bulges along margins which had the effect of steepening margins and decompressing the upper mantle beneath the bulges. A substantial increase in circum-Mediterranean volcanic activity began at this time. Subsequent evaporative drawdown further accelerated mantle decompression. With the loss of water above the accretionary prisms, they flattened and incorporated thick bodies of the surrounding halite. Vergence is seen in both outward and inward directions as they flattened. The increasing accumulation of halite in the deepest regions and dissolution in exposed regions accentuated basinward tilting. Halite flowed from its margins into folds and thrusts as it was still accumulating and before any Pliocene and Pleistocene overburden. Lack of tephra in Pliocene sediments indicates that volcanism diminished following the Zanclean flooding.

**Poster**

## Extensional shear bands in HP-LT metamorphic rocks in the Talea Ori, central Crete, Greece

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In central Crete, the contact between the high-pressure low-temperature (HP-LT) metamorphic Talea Ori unit and Phyllite-Quartzite unit sensu stricto (PQ s.str.) is characterized by an extensional ductile shear zone. We traced the shear zone along the ca. 20 km long contact of the PQ s.str., forming the hanging wall and the Talea Ori unit, forming the footwall. In both units, similar albite porphyroblasts formed during Alpine metamorphism and carbonaceous material in schists shows a similar degree of graphitization, indicating peak metamorphic temperatures of 380–400 °C. This confirms that both units were already in contact during peak metamorphism. The tectonometamorphic characteristics indicate that the two units were juxtaposed during top-to-the-South shearing, with the PQ s.str. structurally overlying the Talea Ori unit. The shear zone at the contact is characterized by extensional shear bands that show top-to-the-north shear sense with the northern block being systematically down faulted. Shear band cleavages (C'-type) indicate a consistent shear sense. Associated discordant quartz veins occur along shear band boundaries and boudin necks. Their microstructures indicate dislocation glide, recovery and recrystallization at temperatures of at least 300–350 °C, which is close to peak metamorphic temperatures for central Crete. The deformation of the metasediments was mainly by dissolution-precipitation creep. Given the association of the discordant quartz veins with shear bands, the shear zone was activated at nearly peak metamorphic temperature, marking an early stage during exhumation. The shear zone is therefore interpreted to mark the onset of exhumation from peak metamorphic conditions. This study demonstrates the importance of extensional ductile shear zones for the exhumation of HP-LT metamorphic rocks in central Crete.

**Poster**

## U-Pb and Lu-Hf isotopic data from detrital zircons in Late Carboniferous and Late Triassic sandstones used to determine provenance and test alternative tectonic models of the tectonic setting of the Anatolide and Taurides, S Turkey

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The Anatolide continental crust of S Turkey is believed to represent part of the N-Gondwana margin since Late Triassic but its previous tectonic setting, especially for the Carboniferous, is debatable. New U-Pb radiometric age dating and Lu-Hf isotopic analysis of detrital zircons from Carboniferous and Triassic sandstones from the Anatolide and/or Tauride continental blocks are used to infer sediment provenance and test alternative tectonic models.

Carboniferous sandstones were analysed from allochthonous units located in the Aladağ nappes (E Taurides), the Konya Complex (Anatolides), and the Karaburun Mélange (Aegean region). Late Triassic sandstones were also analysed from the Üzümdere and Kasımlar Formations (Tauride Autochthon) and from the Güvercinlik Formation (Karaburun Peninsula). A NE African source is inferred for the Aladağ Nappe and the Konya Mélange, in which prominent zircon populations occur at 0.5-0.7, 0.8 and 0.9-1.1 Ga. A contrasting NW Africa-type provenance for the Karaburun Mélange is characterised by ~2 Ga zircons and an absence of Tonian-Stenian zircons. Prominent Devonian-aged zircon populations mainly exhibit positive $e_{Hf(t)}$ values that differ significantly from the Devonian igneous rocks of the Sakarya continental margin arc (Pontides). The Late Triassic sandstones from the Tauride Autochthon and the Karaburun Peninsula exhibit similar Precambrian zircon populations to the Late Carboniferous sandstones. However, Palaeozoic and Early Mesozoic zircons are relatively abundant in the Triassic sandstones. Triassic zircons occur in one sample from the Kasımlar Formation, in which Cambrian and Ordovician-aged zircons predominate. In contrast, Devonian and Carboniferous zircons are more abundant in the Late Triassic sandstones of the Karaburun Peninsula. The Late Palaeozoic zircon populations are explained by derivation from an Armorican terrane assemblage within central Europe. Zircons of similar NW African provenance in the Late Triassic sandstones of the Karaburun Peninsula reflect reworking and mixing with NE African craton-derived detritus.

The isotopic data are inconsistent with tectonic models that infer the presence of a late Carboniferous magmatic arc along the Anatolide margin. Also, the absence of Eurasian-derived zircon populations opposes the existence of a Triassic suture zone between the Tauride and Anatolide continental blocks. We infer that Palaeotethys sutured in the Aegean region to the west during the late Carboniferous leaving an eastward-widening oceanic basin to the east in which Cadomian arc-derived siliciclastic sediments accumulated. The Anatolide-Tauride continental margin represented by the Konya Mélange >500 km to the east of the inferred Aegean suture zone received only NE Gondwana-derived detritus.

This work was supported by TUBİTAK, project no 111R215

**Talk**

## Tracing Triassic arc magmatism and related provenance variation along the Palaeotethyan active margin: Combined U-Pb and Lu-Hf isotopic evidence of detrital zircons in sandstones from the Tokat Massif (central Pontides) and the Ankara Mélange (central Anatolia)

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Using U-Pb-Hf isotopic analysis, detrital zircons have been newly studied from sandstones of the Permian-Triassic active continental margin in northern Turkey, represented by exposures of the Karakaya Complex in the Tokat Massif and the Ankara Melange. The main aim is to determine if Triassic arc-type source rocks, which characterise the sandstone provenance in the type Karakaya Complex area (Biga Peninsula, western Pontides) also contributed sediments to the active margin further east, and to develop a regional synthesis.

The resulting analytical data indicate that Triassic arc-type magmatic source rocks supplied sediment all along the active margin, a distance of >1000 km. In addition to Triassic arc-type source rocks, Permo-Carboniferous and Devonian igneous rocks also supplied detritus to the sandstones all along the active margin.

Despite many similarities, significant changes in provenance appear eastwards. First, the relative abundance of Precambrian zircons increases considerably in the east. Secondly, the melts that formed the Triassic and Late Palaeozoic igneous source rocks mixed with much older, Neoarchean to Palaeoproterozoic-aged crust, unlike the source rocks of the westerly (type) area. Thirdly, the Hf data indicate that, in addition to old crust, juvenile crust formation took place during Late Palaeozoic-Early Mesozoic time and was recycled during subsequent magmatic episodes. The overall isotopic characteristics of the Karakaya Complex sandstones are consistent with an increase in crustal thickness of the source area from west to east.

The new isotopic data suggest that the maximum age of deposition of most of the sandstones in the Tokat Massif and Ankara Melange is Norian (Late Triassic). Also, some units that were previously considered to be Palaeozoic, (i.e. Geyraz Formation; Tokat Massif) should instead be Late Triassic. The maximum depositional age of the structurally uppermost melange unit in the Tokat Massif (Karasenir Formation), which was considered to be Silurian, is Permian based on the new isotopic data.

Our results demonstrate that a Triassic continental margin arc was well developed along at least 1000 km of the Palaeotethyan active margin in Turkey. However, no trace of this arc is known from north of the Pontides or from the Anatolide-Tauride block to the south. Possible explanations are that the Triassic arc was subducted, displaced laterally or concealed by thrusting related to later collisional tectonics.

This work was supported by TUBİTAK, project no 115Y215

Talk

## Deformation history of the Cycladic Blueschist unit (Greece)

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This work summarizes the deformation history of Cycladic Blueschist unit (CBU) using structural and petrological data from several areas in central-south Aegean region. The CBU mainly consists of metasedimentary and metavolcanic rocks and has been affected by an Eocene blueschist to eclogite facies metamorphism, followed by greenschist facies re-equilibration at the early Miocene. It is emplaced via a major ductile thrust over a Basal marble-rich unit, which was affected by mild blueschist facies metamorphism, whereas it's upper boundary is defined by a large-scale normal sense detachment. The hanging-wall of the latter is occupied by crystalline rocks showing no evidence of Alpine HP-metamorphism. Based on this tectonic configuration several studies argue that the exhumation of the CBU was achieved by ductile or wedge extrusion. However, the sense of extrusion remains controversial and the understanding of the deformation history of the CBU is critical to resolve this controversy.

The ductile deformation history of the CBU comprises two main phases. The first phase is associated with internal nappe stacking in the CBU. In Andros and Evia, this phase led to the emplacement of the Ochi and Makrotantalo nappes over the North Cycladic nappe (also referred to as Styra or Lower unit). In other islands (e.g., Sifnos and Syros), this phase resulted to the repetition of the original pile. Structural data coupled with mineral chemistry data of zoned sodic amphibole grains implies that this thrust movements occurred before or contemporaneously with the peak metamorphism. Available kinematic data for this phase generally reveal E- to SE-directed thrusting. The second main phase is penetrative throughout the CBU and is represented by a shallowly dipping planar fabric and an associated NE-trending stretching lineation. This planar fabric is typically axial planar to outcrop- to kilometer-scale NE-trending folds and varies in intensity from a spaced cleavage to a mylonitic foliation. Variation in foliation intensity has mainly resulted from the localization of deformation. In northeast Cyclades and Evia, deformation is localized into major NE-directed shear zones, which cut up-section in their transport direction and restack the early thrust sequence. Amphibole mineral chemistry analyses indicate that these shear zones formed during the progressive decompression of rocks from the stability field of glaucophane to that of actinolite. The SSW-directed shearing during exhumation is observed in the upper structural levels of the CBU (e.g. south Cyclades). Based on the aforementioned data, tectonic models suggesting SW- or NE-directed extrusion are critically discussed.

Talk

## The Eo-Cimmerian evolution of the External Hellenides: Constraints from microfabrics and U-Pb detrital zircon ages of Upper Triassic (meta)sediments (Crete, Greece)

**Gernold Zulauf[1], Wolfgang Dörr[1], Linda Marko[1], Jochen Krahl[2]**

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The lower nappes of Crete are attributed to the External Hellenides and consist of Carboniferous to Triassic sediments and volcanics, that evolved in different settings of the Paleo- and Neotethys reams. The rocks of the Plattenkalk and Trypali Unit were deposited along the southern and northern passive margin of the Neotethys, respectively. Permian opening of the Neotethys resulted in Cimmeria that was rifted off from Gondwana and drifted towards the north.

The Phyllite-Quartzite Unit s.str. developed since the Carboniferous along the passive margin of Gondwana (southern Paleotethys). As this margin remained passive also after the opening of the Neotethys, the Permian to Triassic deposits of the Phyllite-Quartzite Unit s.str. were still deposited in a passive-margin setting until the Paleotethys was closed in the Ladinian. The back-arc deposits of the Tyros Unit, on the other hand, developed on top of a Variscan basement along the active margin of Eurasia (northern margin of Paleotethys).

The volcano-sedimentary records and the age spectra of detrital zircons of the Tyros and the Phyllite-Quartzite Unit s.str., suggest that their different settings persisted as long as the Paleotethys was open, but approximated in Ladinian times, when Cimmeria and Eurasia collided and the Paleotethys was closed. This assumption has been verified by new provenance data of Norian clastic sediments of the Tyros Unit (Toplou Beds) and of the Phyllite-Quartzite Unit s.str. (Mana Beds). The type of clastic grains and the ages of detrital zircons indicate a similar source of both units dominated by (1) Cryogenian and Tonian/Stenian basement, (2) low grade Cadomian basement, and (3) Ladinian/Carnian magmatic rocks. The Carnian zircons in the Norian Tyros Unit (223 ±7 Ma) and in the Norian Phyllite-Quartzite Unit s.str. (223 ±5 Ma) are strong evidence that the basins of both units were situated close together. Subsequent to Ladinian collision, the Carnian to Norian strata of both units were deposited in adjacent interrelated shallow-marine to lacustrine basins, the deposits of which are characterized by black shales, reddish bauxite-type pisolites and badly sorted sandstones/conglomerates supplied from nearby pre-Ordovician East-Gondwana derived basement. The Variscan basement towards the north was largely drowned in Upper Triassic times as is indicated by only few Variscan-aged zircons in the Carnian/Norian Tyros rocks.

Based on the new data, it is concluded that the Cimmerian orogeny ceased prior to the Norian in the Hellenides, whereas orogenic activity was still active further to the east in the Sakarya domain of Turkey.

# 3c) The Alpine-Mediterranean chain – looking from surface to depth, and back in time

Talk

## Dry valley race: What geomorphology tells us about active deformation in the Adria-Eurasia collision zone

**Peter Biermanns**[1], **Benjamin Schmitz**[2], **Janis Pingel**[2], **Kamil Ustaszewski**[2], **Kujtim Onuzi**[3], **Klaus Reicherter**[1]

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Sets of c. coastline-parallel (WNW-ESE striking) anticlinal ridges are shaping the foreland of the tectonically active Dinarides-Hellenides fold-and-thrust-belt in NW Albania and S Montenegro. Connecting in the NNW to the topographically higher mountains in Montenegro, they are overlooking extensive alluvial plains in Albania as isolated elongate hills. The partly overturned anticlines consist of Upper Cretaceous to Middle Eocene limestone (with a hiatus of Lower Eocene, marked by a locally preserved bauxite horizon). Folded Upper Eocence flysches and quaternary alluvial sediments occur in the synclines. Geomorphological features such as dry valleys ('windgaps') give indications about the anticlines' genesis and recent modes of tectonic movement. Geometrical relations and elevations of present day gorges and dry valleys allow for (i) reconstruction of changing rivers courses (particularly Drini River in Albania), (ii) relative age dating of repeated windgap formation per single anticline and (iii) comparison of uplift rates for individual anticlines. The latter is applicable if elevations of simultaneously formed windgaps differ on opposing anticlines. For an example in Albania we observe hinterland windgaps to be elevated c. 100 m higher than their foreland counterparts. Despite this, the frontal anticlines are topographically higher, broader and exhibit a significantly higher degree of degradation (fracturing, faulting, karstification). Drainage networks and other geomorphic indices (e.g. Mountain Front Sinuosity, Hypsometric curves, Vf Ratio, Stream-Length Index) support these observations and suggest a lower degree of tectonic activity for the frontal anticlines. We interpret these observations as a result of decreasing detachment depths, shallowing ramp angles and differing folding mechanisms towards the foreland, which is in line with our balanced cross-section forward modelling approach. To constrain quantitative uplift rates for the area, we supplement our geomorphological studies with data from shallow drill cores (sampled in windgaps and surrounding alluvial plains) and estimates of slip rates (≤ 0.5 mm/yr) on nearby faults.

Poster

## Some thoughts on the geodynamic and sedimentary evolution of the atlasic domain, Morocco

**El Hassane Chellai**

*Cadi Ayyad University, Morocco*

On the geodynamic and sedimentary level, the evolution of the atlasic domain is part of a global framework that begins with the dislocation of the pangea and the opening of the Atlantic rift expressed in North Africa by the atlasic rifting from the Trias/Lias (CAMP: Central Atlantic Magmatic Province).

This rift aborted the Lias forming what is called an Aulacogen. It is followed by the installation of a carbonate platform extending from the Sinemurian to the Bajocian. The beginning of the oceanic expansion is synchronous with the movements of Africa towards the East and the transpression regime in the High-Atlas.

The opening of the South Atlantic to the Upper Jurassic -Early Cretaceous announces the translation of Africa to the Northeast.

This movement is confirmed from the Upper Cretaceous to the present (alpine phase) with a confrontation with the european plate.

It results in a globally compressed N-S accompanied, initiating in Morocco, the uplift of alpine chains such as the High-Atlas and the Middle-Atlas. The uplift and the relief of the atlasic chain is also influenced by tectonic, salt tectonic,….

Talk

## Active faulting in the eastern Southern Alps-Dinarides – insights from field studies, geophysics, and high-resolution topography data

**Christoph Grützner**

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The eastern Southern Alps-Dinarides region has the highest seismicity in the Adria-Alpine collision zone. Historical and instrumental earthquakes such as the 1511 Idrija Earthquake and the 1976 Friuli event exceeded M6 and caused local devastation and a high death toll. Although moderate to strong modern earthquakes and geodetical techniques allow insights into the regional tectonics, many aspects of the active tectonics in the study area are not well understood. In particular, open questions remain about slip rates of individual faults, their earthquake history, their seismic potential, and the impact of active tectonics on erosion rates. It is not clear if crustal deformation is distributed across many active structures or if single faults take up most of the deformation. Also, the transition between head-on thrusting in N Italy and right-lateral motion on NW-trending faults in Slovenia needs further research. The project 'Earth surface response to Quaternary faulting and shallow crustal structure in the eastern Adria-Alpine collision zone and the Friulian plain' aims to solve these open questions in the framework of SPP 2017 'Mountain building processes in 4D'. In a team of geologists, geophysicists, and geochemists we will investigate the geometry of major active faults, their sense of motion, and how they drive erosion using a set of interdisciplinary tools: a) high-resolution digital elevation models from airborne LiDAR surveys and drones; b) near-surface geophysical surveys to image surface traces and the sub-surface structure of active faults; c) palaeoseismological trenching to determine long-term slip rates, earthquake recurrence intervals, and palaeo-magnitudes; d) the erosional response to active faulting using catchment-wide erosion rates from in situ cosmogenic 10Be in river sediment. Here I present first results from the major NW-striking "Dinaric" faults in Slovenia. Field mapping, the analysis of high-resolution topographic data, and near-surface geophysics reveal that surface-rupturing earthquakes have left traces in the landscape. I document offset morphological features such as offset slopes, displaced alluvial fans, and deformed river terraces. Although no radiometric dating is available so far, the state of preservation of these features indicates that the offsets occurred in the Late Quaternary/Holocene. The most promising sites will be subject to paleoseismological trenching studies in the next phase of the project.

**Poster**

## Subduction channel vs. progressive accretion: Insights from the Western Alps

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The processes leading to the formation of collisional mountain belts like the Western Alps are still unclear in several respects. Different models were developed within the last decades. The subduction channel model (e.g. [1]) implies that the eclogite-bearing parts of such mountain belts represent a tectonic mega-mélange where continental crust from the upper plate is continuously dragged down by oceanic lithosphere in the subduction channel, reaching depths up to (U)HP conditions, and brought back to the surface by return flow in the hanging wall of the subduction channel. In this scenario, a simple paleogeography without microcontinents can still lead to a complicated stacking of continental and oceanic high-pressure units. The age distribution of (U)HP metamorphic continental rocks in such a mega-mélange would be irregular to some extent but finally the ages would become successively younger toward the most internal and structurally highest parts. On the other hand the progressive accretion model (e.g. [2], [3]) is based on the assumption that (U)HP rocks exposed at the earth's surface in collisional mountain belts are the result of repeated accretion or underplating of oceanic and continental crust to the hanging wall of a subduction zone, prograding from internal to external paleogeographic zones, and later exhumation. In this case the oldest U(HP) metamorphic rocks would be located in the most internal and structurally highest units with a trend of successively younger ages toward the external and deeper units. The aim of this study is to test the subduction channel and progressive accretion models using Lu-Hf dating of high-pressure rocks. We review the existing data and present first results of new Lu-Hf data for the HP metamorphism of eclogites from the Western Alps, focusing in particular on the Zermatt-Saas Zone ophiolites and the continental slivers (Monte Emilius etc.). The data, although still incomplete, suggest a regular age distribution with ages decreasing from top to base of the nappe stack, supporting the progressive accretion model. Mélange-forming subduction channels, if they existed at all, were apparently a short-lived phenomenon with a much smaller size than complete collisional mountain belts. The stacking of continental and oceanic units rather reflects paleogeography than mélange mixing.

[1] Gerya, T., Stöckhert, B., (2006). *Int J Earth Sci*, 95, 250–274.

[2] Beltrando, M., Rubatto, D., Manatschal, G., (2010). *Geology*, 38, 559–562.

[3] Angiboust, S., Glodny, J., Oncken, O., Chopin, C., (2014). *Lithos*, 205, 298–321.

**Talk**

## Modeled average elastic anisotropies of upper and lower crustal units in the Alps using crystallographic preferred orientations of rocks of the Adula Nappe (Switzerland) and the Ivrea Zone (Italy)

**Ruth Keppler[1], Michael Stipp[2], Michael J. Schmidtke[1], Jacek Kossak[1], Niko Froitzheim[1]**

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As seismic imaging techniques are rapidly advancing, knowledge of elastic anisotropies of rocks in collisional orogens becomes increasingly important. Elastic anisotropy of rocks is to a large part caused by crystallographic preferred orientation (CPO) of their constituent minerals, which in turn forms during deformation. The Alps in particular experienced a complicated tectonic history and consist mainly of highly deformed rock units. There are many uncertainties concerning the structures in deeper parts of the Alps and knowledge of the seismic properties of the rocks at depth to unravel deep structures is therefore essential. One of the problems in using elastic anisotropy data, modeled from natural rocks is the heterogeneity of the crust in terms of composition as well as fabric and especially CPO of the constituent minerals.

In this study, we model elastic anisotropies of several 'average rocks' for both the upper and lower crust in the Alps. Natural samples were collected in the Adula Nappe in the central Alps, representing typically deformed upper Alpine crust, and the Ivrea-Zone in the western Alps representing Alpine lower crust and upper mantle. The CPO of these samples was determined by time-of-flight neutron diffraction at the SKAT diffractometer in Dubna (Russia). From a selection of 30 rock samples representative CPOs of different mineral phases in the most common lithologies were picked. Volume percentages of the different mineral phases in each lithology were determined. The characteristic CPOs and volume percentages were used to calculate elastic anisotropies of 'average rocks' representative of different upper and lower crustal lithologies.

For the upper crust we distinguish between strongly and moderately deformed orthogneisses as well as paragneisses. The modeled paragneiss shows an elastic anisotropy of 8.5%. The highly and the moderately deformed orthogneisses yield 4.5% and 2% elastic anisotropy, respectively. Naturally, these results are representative of the highly metamorphic units of the Alps. For the lower crust we distinguish between gabbro and hornblende-gabbro, both showing elastic anisotropy of under 2%. The elastic tensors of each 'average rock type' can be used as input parameters in geophysical models. However, it has to be kept in mind that a very heterogeneous crust was averaged and a comparison to elastic anisotropy data of natural rocks remainsis essential.

**Talk**

## Calculating elastic anisotropies of rocks from oceanic and continental crust and the upper mantle from the Western Alps

**Michael Jared Schmidtke[1], Ruth Keppler[1], Nikolaus Froitzheim[1], Michael Stipp[2]**

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Seismic imaging methods provide an increasingly higher resolution towards greater depth. However the geotectonic interpretation of these images is only possible with precise data on petrophysical properties (e.g. elastic anisotropies) of the rocks involved. In the olivine dominated mantle, the anisotropies mainly result from the strain-induced crystallographic preferred orientation (CPO) of olivine. In the polymineralic crust the situation is more complicated. CPOs of all constituent mineral phases largely contribute to the overall seismic anisotropy of the rocks.

In the context of the international AlpArray/4D-MB-project, this study focuses on collecting anisotropy data of different lithologies involved in a representative cross section through the Western Alps. The Western Alps display a wide variety of metamorphic and unmetamorphic rocks from diverse structural levels of the earth's crust and upper mantle as well as of different paleogeographic origins. In order to obtain representative elastic anisotropies from oceanic crust, continental lower crust and upper mantle, samples were collected from two different locations in the Italian Western Alps. In the Lago di Cignana area, eclogites and blueschists of oceanic origin (Zermatt-Saas-Zone) are exposed next to metasediments of the Combin-Zone. Near Finero we sampled lower crustal rocks and mantle peridotites of the Ivrea Zone.

The CPOs of the constituent mineral phases of these samples were measured at the Joint Institute for Neutron Research in Dubna (Russia) using time-of-flight neutron diffraction, to gain representative bulk textures. Using these CPOs and single crystal elastic anisotropies the petrophysical properties of the samples were modelled. Micaschists and calcschists from the Lago di Cignana locality, show P-wave-anisotropies of 4,2% and 4,1% respectively. Both samples display strong mineral dominated textures. Further preliminary results for the Finero peridotites, Lago di Cignana metabasites, as well as other lithologies will be presented and discussed.

**Talk**

## 3D Structural Model – Preliminary results from a gravity constrained model of the Alps

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This work constitutes the preliminary results from the first phase of INTEGRATE, a project lying within the scope of the SPP: Mountain Building in 4-Dimensions (MB 4-D). Although the crustal and sub-crustal structures of the Alps are some of the best studied of any orogen in the world, different hypotheses still exist regarding plate architecture and the nature of the subduction system. Rheological configurations of the different crustal units and lithospheric mantle, isostasy in the orogen-foreland system, and variations of flexural rigidity along and across the mountain belt, at the present-day, poorly constrained with relation to spatial patterns of seismicity. The primary goal of INTEGRATE is to provide insights into these questions by generating a gravity constrained, 3D structural model of the Alps and their foreland basins, so that a lithospheric temperature field can be calculated and ultimately the distribution of deformation and seismicity derived across the whole region.

Here we present a first 3D structural model of the entire Alpine orogen, constructed from an integration of all publicly available geoscientific observations on the study area. Our model will be constrained by gravity fields, and the results of previous models generated using similar techniques, in regions that overlap our study area, such as the Rhine Graben, the Molasse Basin and the Po Basin. Additionally, it will benefit from current efforts by the AlpArray Gravity research group to create high resolution terrestrial gravity fields of the region. A combined model such as this will provide estimates of flexural rigidity, loads, gravitational potential energy and stresses in the different crustal bodies and, additionally, allow testing of existing isostastic models of the lithosphere. These 3D models have the potential to be used as a reference for other types of data processing and are a crucial step forward in deciphering how deep-seated mass changes affect the evolution of an orogen.

# Topic 4: Dynamics of core and mantle on Earth and Other Planetary Bodies

## 4a) Magmatic processes and their geochemical signatures on Earth and other planetary bodies

Talk

### Eclogite in the lithosphere and asthenosphere: Chemical and redox effects

**Sonja Aulbach**

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Some compositional heterogeneities of the convecting mantle are due to recycling of crustal material with an average age of ~2 Ga and thus may have involved ancient oceanic crust (OC). Mantle eclogite suites typically form part of the xenolith inventory carried by cratonic kimberlite magmas and have Palaeoproterozoic to Mesoarchaean ages. They have OC protoliths reflecting a diversity in source compositions and degree of magmatic differentiation. The resulting differences in chemical composition and redox budget contribute to the rich elemental, isotopic and redox variability of the lithospheric mantle, which captured part of ancient subducting slabs, and of the convecting mantle source into which the remainder was deeply recyled.

The recent development of eclogite oxybarometers has led to renewed interest in obtaining high-quality $Fe^{3+}/Fe^{total}$ in eclogite garnet ± clinopyroxene, from which $f_{O2}$ relative to the fayalite-magnetite-quartz buffer ($\Delta \log f O_2$) can be calculated. These nascent data-sets indicate that enrichment due to oxidative metasomatism by kimberlite-like melt leads to a poorly defined increase in $Fe^{3+}/Fe^{total}$. Nevertheless, some mantle eclogite suites retain a broad negative correlation of $Fe^{3+}/Fe^{total}$ with Eu*, as expected for incompatible behaviour of $Fe^{3+}$ in igneous (here plagioclase-rich) cumulates. This testifies to some robustness of Fe speciation in mantle eclogites, despite their antiquity. Combined with the low V/Sc (a redox proxy) of unmetasomatised eclogites with little differentiated protoliths, the low estimated bulk eclogite $Fe^{3+}/Fe^{total}$ (e.g. ~0.03 for eclogites from the Kaapvaal craton) compared to modern OC (~0.12) suggests a more reduced Archaean convecting mantle, with accordingly shallower depths to metal saturation or the operation of carbonate redox melting ($2\ Fe_2O_3 + C = 4\ FeO + CO_2$).

Further reduction upon pressure increase and compositional variability lead to $\Delta \log f O_2$ in eclogites ranging from ~0 to -4.6 at lithospheric mantle pressures (~3 to 8 GPa), similar to – but not imposed by – the redox variability recorded by cratonic peridotites. At these conditions, refractory graphite/diamond will be the stable carbon species and $CO_2$ contents in melts are largely <10 wt%. Thus, ancient OC provided no oxidising power and slab-derived carbonatites, from which diamond could crystallise through redox freezing in the deep upper mantle or transition zone, did not form. Conversely, there may be a role for $CH_4$-rich fluids in subducted OC, which could facilitate “hydrous redox melting” ($CH_4 + O_2 = H_2O + C$) rather than “carbonate redox melting” or freezing.

Talk

### No evidence for Transition Zone metamorphism in diamondiferous ophiolites

**Chris Ballhaus**[1], **Raul O.C. Fonseca**[2], **Alessandro Bragagni**[2], **Richard Wirth**[3], **Willibald Pröll**[4], **Anja Schreiber**[3], **Jens Barosch**[2]

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Until recently it was accepted that ophiolites form at low pressure along intra-oceanic spreading ridges. The identification of ultra-high pressure (UHP) phases in chromitites and harzburgites of ophiolite complexes (coesite, stishovite, diamond) appears to be changing that view. It is now being argued that mantle sections of ophiolites either originate in, or were processed within, the Earth’s mantle at depths as great as 600 km. Furthermore, UHP phases are often found associated with super-reduced minerals including native elements, silicides, carbides, and nitrides. Consequently, it is speculated that the mantle source regions of ophiolites must be super-reduced, so reduced that practically all transition elements would occur in a metallic state ($f_{O2}$ < IW-6).

We find it problematic to rewrite the history of ophiolite genesis based on these mineral assemblages. We suggest that they may be the products of lightning strikes. When a lightning bolt hits solid rock, a plasma is generated in the lightning channel. Since in a plasma oxygen is in a cationic ($O^+$) state, the first condensation reactions that take place when a plasma cools are recombinations of cations with electrons to metallic phases. Lightning can also impose ultra-high pressure, albeit only for seconds. When lightning hits solid rock, a thermal pulse is generated in the lightning channel that may impose extreme shock pressures in excess of 10 GPa if heating is isochoric.

To simulate the effects of lightning strikes on solid rocks, electric discharge experiments are carried out at ultra-high temperature. Tungsten and Fe metal electrodes are drilled inside basaltic and quartzitic rock cuboids bridged in the center by a graphite rod. A surge-current generator is connected charged to 9.9 kV. When the discharge is triggered, a current flows exceeding 30 kA and a plasma is generated. Phases identified when the plasma condenses include metallic Si, Fe-Si alloys, SiC moissanite, W-Ti alloys, and metallic Fe. These phases can condense on any type of surface, hence are not diagnostic of the redox state of the rocks within which they occur. We do not identify diamond because our experiments are quenched too rapidly, but we do synthesize concentric shell fullerenes that may serve as nanoscopic pressure cells to vapour-deposited (CVD) diamonds.

**Poster**

## The Highly Siderophile Elements and $^{187}Os/^{188}Os$ signatures of the French Massif Central mafic lavas

**Franziska Bellin**[1], **Ambre Luguet**[1], **Robin Strack**[1], **Geoff Nowell**[2]

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The French Massif Central (MC), the largest igneous province of western Europe, belongs to the European Cenozoic Volcanic Province and is associated to the West European-Rift System. Its scattered Early Miocene MC volcanism is related to passive rifting and the Late Miocene-Quaternary volcanic peak is attributed to active rifting (Merle and Michon, 2001), which is evidenced by an upper mantle thermal anomaly (Sobolev et al., 1997) likely triggered by an asthenospheric flow generated by the subduction of the European plate under Africa and the Alps formation (Merle and Michon, 2001).

A prior geochemical and isotopic investigation of the lithophile element systematics on a representative collection of the MC mafic lavas (Rosca et al., 2013) revealed that the FMC mafic lavas from the eastern volcanic regions (Deves, Velay) are in average richer in alkali ($K_2O+Na_2O$: 5.23-5.87 vs. 4.00-5.57 wt.%) and in trace elements (e.g., $La_N$=63.5-100 vs. 44-80, normalisation after McDonough and Sun, 1995) when compared to the western ones. The Sr-Nd-Hf isotopic signatures are unradiogenic, with the eastern lavas being more unradiogenic (e.g., respectively 0.703050-0.703615 vs. 0.703314-0.704080 for $^{87}Sr/^{86}Sr$ and 0.282996-0.283019 and 0.282893-0.282953 for $^{176}Hf/^{177}Hf$). To better understand the origin of these geochemical and isotopic differences, twelve samples from both the east and west FMC, previously investigated by Rosca et al (2013), were further analysed for their highly siderophile elements (HSE: Os, Ir, Ru, Pt, Pd, Re) and their Re-Os isotopic signatures.

The FMC mafic lavas show a typical melt-like HSE patterns characterised by an overall positive slope from Os to Re. While the eastern and western mafic lavas HSE patterns overlap (as for the trace elements), the western samples appear to be in average HSE-richer. On the other hand, apart from one western mafic lavas, the $^{187}Os/^{188}Os$ ratio of the MC mafic lavas are all radiogenic, with the western ones being in average more radiogenic.

The HSE and $^{187}Os^{188}Os$ signatures confirm then the lithophile elements based investigations and support the existence of geochemical and isotopic differences between the east and west MC mafic lavas. This may reflect either the tapping of two different mantle reservoirs or alternatively the variable contribution of 2 components (e.g., peridotite and pyroxenite) from one single mantle reservoir beneath the French Massif Central.

*Merle and Michon (2001), Bull. Soc. Geol France 172, 213*

*Rosca et al. (2013), Basalt 2013 Conference, Cenozoic Volcanism in Central Europe, Görlitz, Germany.*

*Sobolev et al., (1997), Tectonophysics 275, 143.*

**Talk**

## In search for ancient mantle heterogeneities in the Eifel plume: new insights from high precision $^{182}W$ measurements

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During the last years, the short lived $^{182}Hf$ - $^{182}W$ isotope-system has become a powerful tool identifying ancient differentiation events on Earth [1]. Terrestrial $^{182}W$ isotope anomalies in Archean rocks were either explained by incomplete addition of late veneer [1] or as a vestige of early silicate differentiation events [2]. Recent studies have also revealed small $^{182}W$ anomalies in young ocean island basalts (OIBs), suggesting the persistence of mantle reservoirs that remained isolated since the Hadean [3]. These studies are in line with noble gas approaches that indicate ancient, undegassed and primitive mantle sources for some OIBs [4], and also for intraplate volcanic rocks of the central European volcanic province (CEVP) [5].

To further evaluate putative mantle heterogeneities in volcanic rocks from the CEVP we performed high precision $^{182}W$ and trace element measurements on selected volcanic rocks from the CEVP, focusing on primitive mafic rocks from the Eifel volcanic field (W- Germany). Our sample set comprises all different compositional groups of the East and West-Eifel fields, respectively [6]. All studied samples display canonical W/Th ratios (0.03-0.18) and were measured for the long lived radiogenic-isotope-composition Sr, Nd and Hf and exhibit a moderately enriched mantle signature, intermediate between PREMA and HIMU. Measured $^{182}W$ isotope compositions from the intraplate Eifel volcanics are indistinguishable from the present-day mantle and span a range in $\mu^{182}W$ from -3 to +3ppm with uncertainties generally better than ± 4ppm (95% conf. Limit). Our results are therefore apparently not consistent with Xe isotope data arguing for an ancient, undegassed source of the Eifel mantle plume [5]. However, this apparent discrepancy might be explained by a late isolation of the Eifel plume source (<4.50 Ga) when $^{182}Hf$ was already extinct. Alternatively, the Eifel plume source may be older, but may not have undergone significant elemental Hf/W fractionation to generate measurable $^{182}W$ anomalies.

[1] Willbold et al. (2011) Nature 477, 195-198, [2] Toboul et al. (2012) Science 355, 1065-1069, [3] Mundl et al. (2017) Science 356, 66-69, [4] Mukhopadhyay et al

(2012) Nature 486, 101-104, [5] Caracausi et al. (2016) Nature 533, 82-85, [6] Mertes, H.& Schmincke, H. -U. (1985): Contrib. Mineral. Petrol., 89; 330-345

Talk

## Revisiting the primitive mantle abundances of the moderately volatile elements Sn and In

**Maria Kirchenbaur, Alessandro Bragagni, Raùl Fonseca, Carsten Münker**

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Among the moderately to highly volatile elements, Sn and In are particularly interesting because of their geochemical properties. Tin is prevalent in two oxidation states (2+ and 4+) and behaves like a lithophile element during partial mantle melting, being similarly incompatible as the MREE. Indium is more compatible than Sn, is chalcophile, and has a crust/mantle enrichment factor of three. Supposedly constant Sn/Sm of 0.32 and In/Y of 0.003 in mantle-derived basalts were considered representative of Earth's primitive mantle (PM; 1, 2) and were thus subsequently utilized in estimates of depleted and primitive mantle abundances (e.g., 3, 4).

We present a comprehensive dataset of high-precision Sn and In concentrations for well-characterized samples from Earth's major silicate reservoirs, including a large suite of mantle peridotites, as well as MORB, intraplate basalts and some meteorites. Concentrations of Sn and In were obtained on the same digestions using isotope dilution and MC-ICP-MS (5).

During partial melting of MORB mantle sources, the Sn content correlates with the degree of partial melting of the mantle source. Moreover, the behavior of Sn and In is mainly controlled by clinopyroxene. Our preliminary results imply a rather uniform Sn/Sm of ~0.27 for the mantle source(s) of MORB whereas depleted mantle samples can display Sn/Sm of up to 3.5. Our results show, that inasmuch as the behavior of Sn is concerned, there is a clear decoupling between mantle residue and basaltic magmas, where the former show fractionation between Sn and its geochemical proxy Sm, and the latter suggest that these two elements are similarly incompatible. Our results indicate that the budget of Sn in basalts cannot be solely the result of partial melting, and that additional processes are needed to fully explain the behavior of this element in magmatic processes. Moreover, the canonical Sn/Sm ratio of the bulk silicate Earth is revised, with implications to the establishment of moderately volatile element abundances in the early Earth.

(1) Jochum et al., 1993; (2) Yi et al., 1995 (3) Salters & Stracke, 2004; (4) Palme & O'Neill, 2013 (5) Kirchenbaur et al. (2018)

Talk

## Titanium coordination chemistry and oxidation state during lunar magmatism and ab initio modelling of mass-dependent equilibrium isotope fractionation

**Felipe P. Leitzke[1], Raúl O.C. Fonseca[1,2], Jörg Göttlicher[3], Ralph Steininger[3], Sandro Jahn[2], Clemens Prescher[2], Markus Lagos[1]**

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Lunar basalts are products of mantle partial melting under more reducing conditions when compared to the expected for the Earth's upper mantle. Alongside Fe, Ti can be a major element that is redox-sensitive during lunar magmatic processes. Here, we report new Ti K-edge X-ray absorption near edge structure (XANES) measurements on a wide range of minerals (pyroxene, olivine, Fe-Ti oxides) and basaltic melt compositions involved in partial melting of the lunar mantle and provide insights into mechanisms that may control the resolvable differences in the Ti isotope composition of terrestrial and lunar samples. Experiments were conducted in 1 bar gas-mixing furnaces at temperatures between 1100 and 1300 °C and $fO_2$ from air to two orders of magnitude below the Fe-FeO redox equilibrium. Run products were analyzed via electron microprobe and XANES Ti K-edge measurements. Typical run products had large (> 100 µm) crystals in equilibrium with quenched silicate glass. Ti K-edge XANES spectra show a shift in energy for the absorption edge features from oxidizing to reducing conditions and yield an average valence for Ti of 3.6, i.e., an average $Ti^{3+}/\sum Ti$ value of ca. 0.4 for crystals at IW-1.5 to IW-1.9. Silicate glasses show that Ti is exclusively tetravalent. Overall $Ti^{3+}/\sum Ti$ considering the modal abundance of silicate glass and crystals is 0.11±0.02 at IW-1.5 to –1.9. Pre-edge peak intensities also show that the coordination number of Ti varies from an average V-fold in silicate glass to VI-fold in the Fe-Ti oxides and a mixture between IV and VI-fold coordination in the pyroxenes and olivine. *Ab initio* calculations of mass-dependent Ti equilibrium isotope fractionation in karrooite and pyroxene considering different Ti oxidation states (3+ and 4+) and coordination number (IV and VI-fold coordination) were carried out based on density functional theory, molecular dynamics and a pseudo-frequency analysis method. The largest fractionation factor ($^{49}Ti/^{47}Ti$) observed is when $Ti^{4+}$ is incorporated into pyroxene replacing Si in the tetrahedral site (IV-fold), which may occur in Al-poor systems in nature, even though the amount of $Si^{4+}$-$Ti^{4+}$ substitution in the T-site is still debatable in lunar pyroxenes. Our results help to better constrain the $Ti^{3+}/\sum Ti$ of the lunar mantle phases during magmatic processes and provide first insights into the control mechanisms of mass-dependent Ti isotope fractionation in the context of lunar magmatism.

Poster

## Age and origin of Researcher Ridge in Central Atlantic

**Xiaojun Long[1], Jörg Geldmacher[1], Kaj Hoernle[1,2], Folkmar Hauff[1], Jo-Anne Wartho[1], Dieter Garbe-Schönberg[2], Ingo Grevemeyer[1]**

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The Researcher Ridge (RR) is a 400 km long, WNW-ESE oriented chain of volcanic structures located on 20 to 45 Ma old oceanic crust on the western flank of the Mid-Atlantic Ridge (MAR) at ~14°N. The origin of the RR is unclear. Proposed models for its formation range from purely plate-tectonic driven, shallow processes (e.g., resulting from migration of a triple junction, Roest and Collette, 1986) to upwelling of a passively-tapped heterogeneity in the upper mantle (as proposed for the South Mid-Atlantic Ridge between the Ascension and Bode Verde Fracture Zones; Hoernle et al., 2011) to an involvement of a deep mantle plume. Interestingly, at the latitude where the RR axis projects to the MAR at 14°-15° N, the ridge axis is bathymetrically elevated and characterized by geochemically enriched basalt, the so called 14°N MAR anomaly (Bonatti et al., 1992; Hémond et al., 2006), suggesting a possible relationship of the geochemical/ melting anomaly of the MAR and the RR formation. In this study, we combine $^{40}Ar/^{39}Ar$ age dating with petrological and geochemical (trace element and Sr, Nd, Hf and Pb double spike isotope analyses) studies of volcanic rocks dredged along an E-W profile of the RR during expedition POSEIDON 379/2 to reveal its elusive origin. Major and trace elements show that lavas both from the RR and 14°N MAR anomaly have similar geochemical compositions, but the RR lavas originated from a source more enriched in incompatible elements, formed by lower degrees of partial melting at a greater depth (garnet stability field) and experienced fractionation at higher pressure (under thicker lithosphere) compared to the 14°N MAR lavas. In addition, $^{40}Ar/^{39}Ar$ age determinations indicate the RR volcanism has a younger age than the underlying oceanic crust. Isotopically, the RR lavas partly overlap with the 14°N MAR anomaly lavas but form a distinct trend towards the global HIMU (high-μ = high time-integrated $^{238}U/^{204}Pb$) end member. Therefore, we conclude that RR was most likely created by a weak mantle plume and the 14°N MAR anomaly is caused by classical plume-ridge interaction as the westward migrating MAR moved over the mantle plume.

Poster

## Highly siderophile elements and 187Os signatures in single grain Base Metal Sulfides of pyroxenites from the External Liguride Peridotite Massif, Italy

**Nora Meides[1], David van Acken[2], Ambre Luguet[1], Alessandra Montanini[3], Riccardo Tribuzio[4]**

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The ophiolites of the Northern Apennine thrust and fold belt represent samples of deep subcontinental lithosphere from an ocean-continent transition in Mesozoic times. The External Liguride (EL) units consist of fertile lherzolites with MOR-type isotopic signatures and diffuse pyroxenite layers. Pyroxenites are a main contributor to mantle heterogeneity, yet their origin and petrogenesis is still disputed. Highly siderophile elements (HSE: Os, Ir, Ru, Pt, Pd, Re) and the Re-Os isotopic system, which are predominantly controlled by base metal sulfides (BMS), are considered powerful tools to study mantle processes offering a different perspective than conventional lithophile trace elements. To better understand the melt-rock interactions in the lithospheric mantle on an individual grain scale, 22 BMS from two EL pyroxenite samples from Monte Gavi and Rio Strega were analyzed for HSE and $^{187}Os/^{188}Os$ signatures.

The Monte Gavi pyroxenite consists of a coarse-grained matrix of Cpx, Opx, Ol and secondary mica. Base metal sulfides occur as abundant (n=30-40 grains per thin section) large grains (up to 400 µm), systematically associated to mica and adjacent chlorite-filled fractures crosscutting the entire sample. They are Py, Pn and Cpy in close to equal proportions (40%:35%:25%, respectively) frequently intergrown with ilmenite and magnetite.

The Rio Strega garnet clinopyroxenite has a fine-grained matrix of Opx, Cpx, Grt, Spl and Plag. Base metal sulfides are as abundant as in the Monte Gavi pyroxenite, smaller in size (50-100 µm) and show a different sulfide assemblage (Po:Pn:Cpy = 55%:25%:20%). They are located at Cpx-Plag grain boundaries showing no association with oxides.

In the BMS, HSE concentrations span over two orders of magnitude, ranging from 1 ppb to 5 ppm, showing an overall broad, positive CI-chondrite normalized HSE pattern (Pd/Ir = 29-59; Re/Os = 2-17). Their $^{187}Os/^{188}Os$ signatures vary from unradiogenic to highly radiogenic (0.1081-0.3745) with one outlier at 1.0062. The pyroxenites, which formed by melt-rock reaction between a silicate melt and a peridotitic protolith, have thus inherited their $^{187}Os/^{188}Os$ signatures at the grain scale from both the mantle residue and metasomatic agent. Additionally, the BMS are comparatively less radiogenic than the respective bulk pyroxenite ($^{187}Os/^{188}Os$: 0.6906 for Monte Gavi, 1.0544 for Rio Strega), suggesting that radiogenic Os, and potentially other HSE, are also significantly hosted by platinum group minerals or silicates.

Ultimately, this study highlights the necessity of considering not only bulk rock isotopic signatures, but also the mineral scale ones, when studying the heterogeneity of the terrestrial mantle.

Talk

## Mantle-derived trace element variability in olivines and their melt inclusions

**David Axford Neave**[1], **Oliver Shorttle**[2], **Martin Oeser**[1], **Stefan Weyer**[1]

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Trace element variability in oceanic basalts is commonly used to constrain the physics of mantle melting and the chemistry of Earth's deep interior. However, the geochemical properties of mantle melts are often overprinted by mixing and crystallisation processes during ascent and storage. Studying primitive melt inclusions offers one solution to this problem, but the fidelity of the melt-inclusion archive to bulk magma chemistry has been repeatedly questioned. Here we present new major and trace element analyses from olivine macrocrysts in the products of two geographically proximal yet compositionally distinct primitive eruptions from the Reykjanes Peninsula of Iceland to provide a novel check of the melt inclusion record. By combining these macrocryst analyses with melt inclusion analyses we demonstrate that olivines have similar patterns of incompatible trace element (ITE) variability to the inclusions they host, capturing chemical variability on both intra- and inter-eruption scales.

ITE variability in olivines from the ITE-enriched Stapafell eruption is best accounted for by olivine-dominated fractional crystallisation. In contrast, ITE variability in olivines and inclusions from the ITE-depleted Háleyjabunga eruption cannot be explained by crystallisation alone and must have originated in the mantle. Compatible trace element (CTE) variability is best described by crystallisation processes in both eruptions. Modest correlations between host and inclusion ITE contents in samples from Háleyjabunga suggest that melt inclusions can be faithful archives of melting and magmatic processes. It also indicates that degrees of ITE enrichment can be estimated from olivines directly when melt inclusion and matrix glass records of geochemical variability are poor or absent. Inter-eruption differences in olivine ITE systematics between Stapafell and Háleyjabunga mirror differences in melt inclusion suites and confirm that the Stapafell eruption was fed by lower degree melts from greater depths within the melting region than the Háleyjabunga eruption.

Although olivine macrocrysts from Stapafell are slightly richer in Ni than those from Háleyjabunga, their overall CTE systematics (e.g., Fe/Mn) are inconsistent with being derived from olivine-free pyroxenites. However, the major element systematics of Icelandic basalts require lithological heterogeneity in their mantle source in the form of Fe-rich and hence fusible domains. We thus conclude that enriched heterogeneities in the Icelandic mantle are composed of modally enriched yet nonetheless olivine-bearing lithologies and that olivine CTE contents provide an incomplete record of lithological heterogeneity in the mantle. Modally enriched peridotites may therefore play a more important role in oceanic magma genesis than previously inferred.

Talk

## Shapes of Rare Earth Element patterns in planetary basalts and their significance

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The usefulness of the Rare Earth Elements (REEs) in geochemistry arises because their partition coefficients between coexisting phases often cover a wide range, but within that range vary smoothly with the ionic radius of their 3+ cations, $r_{REE,}$ Eu and sometimes Ce excepted. The smooth chondrite-normalized REE patterns may be fitted to polynomials in $r_{REE}$ with three to five terms, which can be re-arranged into an orthogonal form:

$\ln([REE]/[REE]_{CI}) = \lambda_0 + \lambda_1 f_1^{orth} + \lambda_2 f_2^{orth} + ......$

where $f_1^{orth}$, $f_2^{orth}$ etc. are themselves polynomials of $r_{REE}$, chosen such that the coefficients $\lambda_0$, $\lambda_1$, $\lambda_2$, etc. are not correlated with each other. This property allows coefficients from different patterns to be compared. The terms have a simple, intuitive meaning: $\lambda_0$ is the average of the logarithms of the CI-normalised REE abundances; the term in λ1 describes the linear slope of the pattern; that in λ2 describes the quadratic curvature, etc.

The large number of REE patterns that can be handled can reveal petrogenetically interesting structures in large datasets that may not be apparent with traditional ways of viewing REE data. For most basalts, fits using only three terms capture REE patterns to better than ±5%. The $\lambda_n$s, or "shape coefficients", enable quantitative comparisons of REE patterns. Especially instructive are $\lambda_2$ vs. $\lambda_1$ diagrams (quadratic curvature versus slope). The usefulness of this approach may be demonstrated using the REE patterns of basalts from different tectonic settings on Earth, and from different planetary bodies.

The fact that REE partition coefficients are also smooth functions of $r_{REE}$ may be exploited using the same orthogonal polynomials. Many mass-balance equations for petrogenetic processes relating observed to initial concentrations, $[REE]_o$, such as fractional melting or crystallization, may be fitted:

$\ln([REE]/[REE]_o) = \psi_0 + \psi_1 f_1^{orth} + \psi_2 f_2^{orth} + ....$

The orthogonality of the polynomials ensures that all $\lambda_n$ and $\psi_n$ terms of the same order n sum independently of all the other terms, such that $\lambda_n = \lambda_n^o + \psi_n$, where $\lambda_n^o$ is the shape coefficient of the source or parent. On $\lambda_2$ vs. $\lambda_1$ diagrams, this approach can relate the shapes of REE patterns in parental basalts to the shapes of their sources, or differentiated basalts to their parental melts, by means of "petrogenetic process vectors" consisting of the $\psi_1$ and $\psi_2$ terms, which plot as vectors on the diagrams.

The method lends itself well to examining hypotheses for the petrogenesis of extra-terrestrial basalts.

Poster

## In-situ iron isotope analyses of olivine and magnetite grains in a melilitite bomb from the Salt Lake Crater

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Iron isotope data from mantle xenoliths are characterized by their variability in $\delta^{56}Fe$, spanning three times the range found in basalts [1, 2, 3], and by the extremely light values of some whole rock samples, reaching $\delta^{56}Fe$ as low as -0.69 ‰ in a spinel lherzolite [3]. Cause to this large range of variations may be metasomatic processes, involving metasomatic agents like volatile bearing high-alkaline silicate melts or carbonate melts [1, 2, 4, 5]. The expected effects of metasomatism on iron isotope fractionation vary with parameters like melt/rock-ratio, reaction time, and the nature of metasomatic agents and mineral reactions involved [6].

To trace the magmatic evolution of rocks by their iron isotope signatures, usually analyses of whole rocks and mineral seperates are used [e.g. 4, 6]. However, diffusion driven processes like chemical exchange between xenocrysts and melt, or interaction of percolating small volume (carbonate) melts with a host rock may alter iron isotope compositions very locally between and within single grains [5, 7, 8]. In a mineral separate analysis, these local signatures will be averaged out.

To reveal variations in iron isotope composition on the micro scale, we performed in-situ iron isotope analyses by femtosecond-laser ablation coupled to MC-ICP-MS on magnetite and olivine grains (with a precision on $\delta^{56}Fe$ of 0.1 ‰, 2SD). The investigated sample is a melilitite bomb from the Salt Lake Crater group at Honolulu (Oahu, Hawaii), showing strong evidence for interaction with a carbonatite melt. While magnetite grains are rather homogeneous in their iron isotope compositions, olivine grains span a far larger range in iron isotope ratios. The variability of $\delta^{56}Fe$ in magnetite is limited from -0.17 ‰ to +0.08 ‰. $\delta^{56}Fe$ in olivine range from -0.66 ‰ to +0.03 ‰, which we interpret as a result of magma mixing between a silicate and a carbonatite magma.

[1] Beard and Johnson (2004) GCA 68
[2] Williams et al. (2005) EPSL 235
[3] Zhao et al. (2012) Chem. Geol. 292-293
[4] Williams and Bizimis (2014) EPSL 404
[5] Zhao et al. (2017) GCA 208
[6] Poitrasson et al. (2013) Contrib. Min. Pet. 165
[7] Weyer and Seitz (2012) Chem. Geol. 294-295
[8] Oeser et al. (2015) GCA 154

Poster

## Pyroxenites as tracers for melt-rock interaction and recycled material in the oceanic mantle

**David Van Acken[1,2], Ambre Luguet[2], Alessandra Montanini[3], Riccardo Tribuzio[4], J. Stephen Daly[1]**

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Pyroxenite layers in orogenic mantle massifs have been interpreted as melt-dominated products of melt-rock interaction in the lithosphere and have been suggested to play a key role in the genesis of basaltic melts. The Ligurian ophiolites in Northern Italy contain abundant pyroxenite layers, allowing for detailed study of their formation mechanisms and interaction with wall rock peridotites. They are considered to represent a portion of the Jurassic Tethyan ocean floor obducted during the Alpine orogeny.

Highly siderophile elements (HSE) and $^{187}Os/^{188}Os$ signatures have been shown to be a useful tool to study melt-rock interaction in the mantle, because of their wide range of compatibility during partial melting and their affinity to sulfides, offering complementary insights compared to lithophile trace elements and their isotope systems. For this study, HSE concentrations and $^{187}Os/^{188}Os$ compositions were analysed in pyroxenites and associated wall rock peridotites from the Mt. Aiona, Mt. Prinzera, Mt. Gavi, and Rio Strega sites of the External Ligurian ophiolites.

The Ligurian pyroxenites show patterns enriched in incompatible HSE such as Pd and Re, supporting a melt-dominated origin from material having undergone previous episodes of HSE fractionation, such as recycled oceanic crust. Radiogenic $^{187}Os/^{188}Os$ values support the notion of long-term Re/Os-enrichment in the source of the parental melts. The associated lherzolites show flat chondrite-normalized HSE patterns, most consistent with a multi-stage history of depletion of incompatible HSE followed by replenishment of these elements to the peridotite budget through interaction with the pyroxenite-forming melts. The HSE patterns and concentrations are consistent with a proposed origin of the pyroxenite layers through partial melting of subducted eclogites, as suggested previously for the Ligurian pyroxenites (e.g. Montanini and Tribuzio, 2015) as well as for other suites (e.g. van Acken et al., 2010). These results reassert the presence of recycled material enriched in incompatible HSE in the form of pyroxenites in the oceanic mantle, and hence potentially in the source for oceanic basalts, with implications for the nature of the source of basaltic melts in the oceanic lithosphere.

Talk

## Carbon solubility in silicate melts coexisting with graphite and a $CO-CO_2$ gas phase

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In the modern Earth, carbon dissolves in magmas mostly as carbon dioxide ($CO_2$) which plays an important role in melting process and volcanic eruptions. The behavior of carbon monoxide (CO) is not well studied, because it is a trace component in volcanic gases. However, under more reduced conditions that likely prevailed in the early history of Earth and Moon, CO may have been an important volatile component. Therefore, in order to understand the behavior of carbon under reducing conditions, we investigated the solubility of carbon in a silicate melt coexisting with both graphite and a $CO-CO_2$ gas phase. In this system, the gas composition is controlled by the equilibrium $2 CO = CO_2 + C$, which also buffers oxygen fugacity. Experiments were carried out with rhyolitic, andesitic and basaltic melts from 2 to 30 kbar and from 1200 to 1500 ˚C. At pressures up to 5 kbar, we directly loaded CO gas into sample capsules that were run in an internally heated gas pressure vessel. A piston cylinder apparatus was used at higher pressures and a reduced $CO-CO_2$ gas phase was produced by loading both graphite and $Ag_2C_2O_4$ into the capsules. Both types of experiments yielded entirely consistent results. Carbon contents in the quenched glasses were quantified by the CAMECA IMS 7f secondary ion mass spectrometer at Tohoku University.

Bulk carbon solubility in all systems studied increases linearly with pressure according to Henry´s law, with melt composition and temperature having only a minor effect on solubility. Overall carbon solubilities are not far away from those observed in equilibrium with pure $CO_2$. However, only a small fraction of total carbon appears to be dissolved in reduced form (i.e. as CO) and this fraction increases from rhyolite to andesite and to basalt. These observations have two important consequences: (1) For a magma ocean coexisting with a reduced, CO-rich gas phase, the amount of carbon dissolved in the silicate melt is not much lower than for oxidizing conditions; (2) on the other hand, the relatively high carbon solubility in silicate melts under reducing conditions makes it rather unlikely that dissolved carbon was driving the fire-fountain-type eruptions on the early Moon. This is because according to our data, the low carbon contents in lunar magmas would not be sufficient to produce high overpressures, if equilibrium with graphite was reached.

# 4b) Materials, structure and dynamics of Earth's deep interio

Poster

## $CaCO_3$ phase diagram studied with Raman spectroscopy at pressures up to 50 GPa and high temperatures and DFT modeling

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The knowledge about the phase stabilities of carbonates is a prerequisite for understanding the presence of carbonates in diamond inclusions and the carbon cycle in the deep Earth. Once phase stabilities of carbonates are known, the elastic behaviour and the relevance for seismology can be obtained.

In our current study [1], the phase diagram of $CaCO_3$ has been revised from 2-45 GPa and 300-3500 K using Raman spectroscopy in laser heated diamond anvil cells. We confirm numerous aspects of earlier studies, including a recent X-ray diffraction study [2] about the stability field of $CaCO_3$-VII. $CaCO_3$-VII is stable at mantle conditions between 25-39 GPa (690-1010 km) [1]. Aragonite and $CaCO_3$-VI are stable up to 25 GPa and 30 GPa, respectively. Based on our experiments at different pressure conditions we conclude that aragonite and $CaCO_3$-VI occur metastably in quasi-hydrostatic pressure conditions at least up to 45 GPa and at ambient temperature. In non-hydrostatic conditions, aragonite begins to transform to aragonite-II around 30 GPa and $CaCO_3$-VI can transform to CaCO3-VII. For the first time we collected Raman data for $CaCO_3$-VII, argonite-II and post-aragonite, carried out mode assignments, and determined the pressure derivatives of frequencies and mode Grüneisen parameters.

In order to qualify that the geophysical significance of phase stabilities of $CaCO_3$ at mantle conditions we calculated the elastic stiffness tensor, bulk moduli and density of aragonite and $CaCO_3$-VII at 25 GPa and of post-aragonite and $CaCO_3$-VII at 40 GPa using DFT. According to our results, the shear sound velocity will increase by 9% across the transitions from aragonite to $CaCO_3$-VII while the shear sound velocity will decrease by -12% across the transitions from $CaCO_3$-VII to post-aragonite. We estimated seismic wave velocities in a pyrolitic mantle model with varying amounts of $CaCO_3$. Our model showed that the phase transitions from aragonite and $CaCO_3$-VII and from $CaCO_3$-VII to post-aragonite give observable changes of the shear and longitudinal velocities in a pyrolitic mantle composition with 2% and 10% $CaCO_3$. Hence the presence of sufficient amounts of $CaCO_3$ in the Earth's mantle would cause a decrease of shear velocity at around 1010 km or an increase of shear velocity at 690 km.

[1] L. Bayarjargal et al., Phys. Earth Planet. Inter. (2018) *281*, 31–45.

[2] X. Li et al., Geophys. Res. Lett., (2018) *45*, 1355-1360.

The authors gratefully acknowledge financial support by the DFG (FOR 2125 "CarboPaT", BA4020/2-1 and RA2585/1-1).

Talk

## The High-Pressure Elasticity of Polycrystalline Stishovite and Seismic Scattering in Earth's Lower Mantle

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Deep reservoirs of silica-rich materials, such as recycled oceanic crust, have been inferred based on geochemical and geophysical observations. For example, scattering of seismic waves in Earth's lower mantle has been attributed to the presence of subducted oceanic crust or silica-rich materials exsolved from Earth's core. These interpretations are based on the expected low sound wave velocities of the high-pressure silica polymorph stishovite. At pressures around 50 GPa, tetragonal stishovite distorts to a ferroelastic orthorhombic phase. This phase transition is predicted to involve a substantial reduction of the shear modulus.

We performed high-pressure X-ray diffraction experiments on sintered polycrystalline stishovite up to pressures of 73 GPa and Brillouin spectroscopy experiments up to 60 GPa. A focused ion beam was used to cut circular disks from a double-sided polished thin section of sintered polycrystalline stishovite. The disks were loaded into diamond anvil cells and surrounded by neon as pressure-transmitting medium. In comparison to stishovite powder or single crystals, sintered polycrystalline stishovite appears to be less compressible below the phase transition with a sharp increase in compressibility at the phase transition. Shear wave velocities as determined by Brillouin spectroscopy, however, follow a smooth increase across the phase transition. We explain these apparent contradictions to earlier studies by the complex elastic and photo-elastic response of polycrystalline stishovite and reconcile our directly determined shear wave velocities with those predicted by a Landau theory approach based on our X-ray diffraction results.

To assess the seismic scattering potential in Earth's lower mantle, we computed the contrasts in seismic properties between silica-rich materials, such as basalt, and pyrolite. Our results show that the phase transition in stishovite gives rise to strong seismic contrasts at conditions of the lower mantle. We further compared the modeled depth profiles of seismic contrasts with the geophysically observed depth distribution of seismic scatterers and found indications for deep silica reservoirs in Earth's lower mantle.

Poster

### Tracing Water in the Transition Zone: From Single-Crystal Elasticity to Seismic Observables

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The transition zone in Earth's mantle is believed to control water transport into Earth's deep interior by acting as a water reservoir. The nominally anhydrous minerals wadsleyite and ringwoodite can incorporate hydroxyl groups in their crystal structures and retain water in Earth's transition zone. Hydration of these minerals affect their physical properties opening the possibility to map mantle hydration from geophysical observations [1,2]. However, attempts to map the hydration state of the transition zone with geophysical remote sensing techniques, including seismology and magnetotellurics, lead to contradicting results [1-4].

We performed high-pressure Brillouin spectroscopy and X-ray diffraction measurements on iron-bearing (Fe/(Mg+Fe) = 0.11) wadsleyite and ringwoodite single crystals. P-wave and S-wave velocities of (nearly) anhydrous wadsleyite and three ringwoodite crystals with different hydration states were determined up to pressures of the transition zone and at simultaneously high-pressures and high-temperatures. For both minerals, hydration reduces aggregate velocities at ambient conditions. With increasing pressure, however, both P-wave and S-wave velocities of hydrous and anhydrous wadsleyite and ringwoodite converge until they become indistinguishable at pressures of the shallow and deeper transition zone, respectively. Our results show that differences in seismic wave speeds between anhydrous and hydrous wadsleyite and ringwoodite potentially remain too small to be detected by seismic tomography.

By combining our results with density and elasticity data for olivine, we computed the acoustic impedance contrasts at the 410-km and 520-km seismic discontinuities. We found the impedance contrast and hence the seismic reflectivity of the 410-km discontinuity to be sensitive to hydration providing an indicator of hydration in the shallow transition zone. Lateral variations in the reflectivity of the 410-km discontinuity might therefore be used to detect pathways of water transport into Earth's deep interior. The impedance contrast at the 520-km discontinuity appears to be less sensitive to hydration.

[1] Huang, X., Xu, Y. & Karato, S.-i. (2005) *Nature* **434** 746-749. [2] Houser, C. (2016) *Earth Planet. Sci. Lett.* **448** 94-101. [3] Yoshino, T., Manthilake, G., Matsuzaki, T. & Katsura, T. (2008) *Nature* **451** 326-329. [4] Mao, Z., Jacobsen, S. D., Jiang, F., Smyth, J. R., Holl, C. M. & Duffy, T. S. (2008) *Geophys. Res. Lett.* **35** L21305.

Talk

### Numerical subduction models in a two-layer mantle: exploring stress-dependent mantle viscosity parameters

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Geodynamic models of subduction often support reconstructions of past, current and future tectonic settings. These models usually implement a simplified linear viscous mantle rheology, where the viscosity is constant and the strain rate varies linearly with the stress, which is a reasonable assumption for low stress conditions. However, subducting slabs form regions of high stress in the mantle, which means that rock deformation will occur by power-law creep. In the case of a power-law rheology, the strain rate varies with the stress to a power $n$ and the viscosity is stress-dependent. Hence, if the mantle has a power-law rheology, the viscosity in the mantle around the slab is reduced, promoting faster sinking of the slab.

Some numerical models of subduction have included a power-law upper-mantle rheology but assumed a linear viscous lower mantle. In spite of the lower mantle being dominated by linear viscous flow, subducting slabs are capable of localizing domains of power-law viscous flow. Hence, geodynamic subduction models should implement a composite linear and power-law rheology for flow in both upper and lower mantle. This requires constraints on mantle properties which are usually derived from experimental petrology and seismological observations. However, the rheological properties of the lower mantle remain poorly constrained due to the uncertainties associated with these sources.

In this study, we use 2D numerical models to explore mantle rheology parameters by analyzing the interaction between a subducting plate and the upper-lower mantle 660 km discontinuity. The models are isothermal, reducing the number of variables in mantle properties to only two: the power-law exponent, which depends on the material, and the transition strain rate (i.e., the second invariant of strain rate at which the power-law viscosity is equal to the linear viscosity).

By exploring the parameter space of the transition strain rate and the power-law exponent, we aim to improve our understanding of how mantle rheology influences subduction modes. For instance, whether or not it can facilitate or hinder slab penetration through mantle discontinuities.

Poster

## Subducting slabs interactions with stratified and stress-dependent viscosity mantle

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Tomography studies reveal a progressive lateral variation of slab configuration along arcs in wide subduction zones, which can be related to mantle stratification. Four distinct types of configurations have been identified: (1) the slab does not penetrate the 660 km discontinuity, 2) the slab sinks through the 660 km discontinuity, (3) the slab stagnates in the top region of the lower mantle, above 1000 km, and (4) the slab sinks into the deep lower mantle. These interactions are commonly analyzed by geodynamic modelling, and it has been observed that the type of configuration is dictated, in part, by slab-mantle density and viscosity contrasts, slab sinking rate and trench motion.

Such models usually assume a simplified linear viscous mantle rheology, where the viscosity is constant and the strain rate varies linearly with the stress. However, subducting slabs form regions of high stress in the mantle, which means that rock deformation will have a power-law rheology component. Some numerical models have included a power-law rheology in the upper-mantle, where the strain rate varies with the stress to a power $n$ and the viscosity is stress-dependent. A power-law rheology mantle means that the viscosity of the mantle around the slab is reduced, promoting faster sinking of the slab. Even though the lower mantle is dominated by linear viscous flow, subducting slabs form localized zones of power-law viscous flow. Hence, geodynamic subduction models should include a composite linear and power-law rheology in all layers of the mantle.

In this study, we use 2D subduction models to explore how slabs interact with stratification in a mantle with stress-dependent rheology. The overarching goal is to relate subduction dynamics with the progressive lateral variations of slab configuration along an arc observed in seismic tomography data. We adopt an isothermal numerical modelling approach (i.e., not accounting for temperature), assuming power-law rheology in a three-layer mantle, divided into upper mantle, mantle transition zone and lower mantle. One advantage of this approach is that it reduces the number of variables in mantle properties to only two: the power-law exponent, which depends on the material, and the transition strain rate (i.e., the second invariant of strain rate at which the power-law viscosity is equal to the linear viscosity). Another advantage is that it isolates the stress-dependent mantle rheology effects on the subducting plate.

Talk

## Probing spin transition at combined high pressure and temperature by optical spectroscopy

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Spin transitions in iron-bearing minerals are often hypothesized to be responsible for seismic and other geophysical anomalies in the Earth's lower mantle. To test this hypothesis, precise knowledge of the pressure ($P$) and temperature ($T$) conditions of spin transitions in lower mantle minerals is required. As of now, only the pressure range of the spin transition in ferropericlase (Mg,Fe)O is experimentally constrained to ~50-60 GPa but only at room temperature. Theoretical studies predict that at high $T$ the pressure range over which spin transitions take place is significantly broadened. As a consequence, geophysical anomalies associated with spin transitions must not be sharp but occur over the range of 500-1500 km in the mantle. Experimental reports on the $P$-$T$ range of spin transitions are very rare[1] as spin transitions are extremely difficult to probe at combined conditions of high $P$ and $T$. For example, x-ray emission and Mossbauer spectroscopies, conventional probes for spin transitions used in mineral physics, both require hour-long accumulations which is difficult to combine with stable laser-heating at $T$ ~2000-4000 K. Here we report on an alternative experimental approach used to detect spin transitions at combined high $P$-$T$ that is based on a direct optical probe of the electronic structure of iron in lower mantle phases. Optical absorption of iron-bearing minerals is sensitive to the electronic structure of iron. Previously, however, the use of optical spectroscopy was limited to room temperature as intense thermal radiation at $T$ > 1000 K diminishes the signal-to-background ratio. Recently we overcame this challenge by developing a novel approach based on a bright nanosecond pulsed optical probe synchronized with a gated detector[2]. This new technology offers a unique window into the spin transitions at high $P$-$T$ at the overall heating time of seconds or less. We will present this new technological development as well as report our most recent results on the $P$-$T$ range of spin transitions in lower mantle minerals.

**Reference**

1. Lin, J. F.; Vanko, G.; Jacobsen, S. D.; Iota, V.; Struzhkin, V. V.; Prakapenka, V. B.; Kuznetsov, A.; Yoo, C. S., Spin transition zone in Earth's lower mantle. *Science* **2007,** *317* (5845), 1740-1743.

2. Lobanov, S. S.; Holtgrewe, N.; Goncharov, A. F., Reduced radiative conductivity of low spin $FeO_6$-octahedra in $FeCO_3$ at high pressure and temperature. *Earth Planet. Sci. Lett.* **2016,** *449*, 20-25.

Poster

## Why the mantle transition zone does not appear to be thinned at plume sites

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Deep mantle plumes and associated high thermal gradients are expected to cause an upward deflection of phase transitions defining the lower-upper mantle boundary and an overall thinning of the mantle transition zone in receiver function data. We use forward calculations of mineral assemblages, seismic velocities, and receiver functions to explain the common absence of these observations through large temperature-dependent variations of seismic velocities in the lower mantle transition zone. At high thermal gradients, primitive mantle compositions display assemblages dominated by majoritic garnet and periclase. Associated seismic velocities would be 5-10 percent lower than for wadsleyite- or ringwoodite-rich assemblages, which are characteristic for thermally undisturbed conditions. The identified low-velocity zone at upwelling sites could cause a miscalculation of the lower-upper-mantle boundary in the order of 20 kilometers. Our results also confirm and explain existing propositions of low velocities in the lower mantle transition zone at plume sites, which are based on the observation of negative conversions in receiver function data in 500-600 kilometers depth.

Talk

## Properties of magmas at depth from $SiO_2$ local structure measured using X-ray Raman spectroscopy

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Melt properties at high pressure are crucial to model the evolution of the deep part of the Earth formation and evolution. $SiO_2$ is the main component of silicate melts in the Earth's deep mantle and controls their network structure and physical properties with pressure. Knowledge of the short-range atomic and electronic structure in melts brings important constraints about their compressibility and viscosity at depth. We measured the O K-edge and the Si $L_{2,3}$-edge in silica up to 110 GPa using X-ray Raman scattering spectroscopy, with a striking match to calculated spectra of the quenched high-pressure melt based on structures from molecular dynamics simulations. Our data show two major discontinuities at high pressure that are related to coordination changes. Between 20 and 27 GPa, at the transition zone (660 km), $^{[4]}$Si species are converted into a mixture of $^{[5]}$Si and $^{[6]}$Si species. Between 60 and 70 GPa, in the lower mantle, a further transition marks the decrease of $^{[5]}$Si species with $^{[6]}$Si becoming dominant above 70 GPa without crossing-over the 6-fold references stishovite and $CaCl_2$ phases up to at least 110 GPa. These two discontinuities are found at the same pressure of change in compressibility and density measured on the same $SiO_2$ glass [1]. The changes of coordination and density measured on $SiO_2$ may have direct influence on the properties of silicate melts at depth with changes in viscosity and partitioning of elements at such pressures. Higher coordination than 6 only takes place beyond 140 GPa corroborating brillouin scattering measurements in agreement with our results with a further increase in density at such pressure. Silicate melts containing network modifiers elements may potentially densify at a lower pressure making magmas neutrally buoyant at the depth of the core-mantle boundary.

[1] S. Petitgirard *et al.*, SiO2 glass density to lower-mantle pressures. *Phys. Rev. Lett.* **119**, 215701 (2017).

Talk

## Seismic constraints on the thermochemical structure of the mantle transition zone

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The subduction of oceanic lithosphere and the rise of thermal plumes from the base of the mantle alter the temperature and composition of the upper-mantle transition zone (MTZ). Over geologic time, mechanical mixing may produce a compositional gradient across the MTZ since basaltic components accumulate preferentially above the 660-km phase transition and melt-depleted, harzburgitic components concentrate below it. I will discuss our recent modeling results that provide seismic evidence for compositional layering in the MTZ in agreement with numerical convection simulations and mineral physics constraints. Our work has focused on North America and Samoa in the southwest Pacific, which are regions characterized by long-term subduction and plume upwelling, respectively. Our analysis is based on the interpretation of velocity anomalies in global seismic tomography and the modeling of P-wave to S-wave conversions recorded by dense continental-scale arrays.

Poster

## Single-crystal elasticity of iron-bearing phase E by Brillouin spectroscopy and seismic detection of water in Earth's upper mantle

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Water-rich minerals are transported into the Earth's interior in subduction zones, where hydrated oceanic lithosphere sinks into the deep mantle. The increases in pressure and temperature during subduction lead to the breakdown of these hydrous minerals, resulting in a release of free fluids capable of triggering both magmatism and seismicity along subduction zones. In cold subduction environments, however, water is thought to be transported to larger depths by Dense Hydrous Magnesium Silicate (DHMS) phases. Among these DHMSs, phase E shows the lowest bulk modulus, suggesting that it might be detectable by seismological investigations that aim at quantifying the amount of deeply subducted water. However, the shear elastic properties of phase E have never been investigated, hampering the possibility of quantifying its presence at depth through the interpretation of seismic velocity heterogeneities detected by seismology.

We synthesized large iron-bearing phase E single crystals in a multi-anvil apparatus at the Bayerisches Geoinstitut. Chemical and structural aspects of selected samples have been accurately characterized by electron microprobe, Mössbauer spectroscopy and single crystal X-ray diffraction analyses. We performed single crystal elasticity measurements using Brillouin spectroscopy and determined the full elastic tensor of phase E. At ambient conditions, we found the Voigt-Reuss-Hill average for the adiabatic bulk modulus to be 95.7(4) GPa, while the shear modulus is 59.4(2) GPa. We derived compressional and shear anisotropies of ~9% and ~20%, respectively. Acoustic wave velocities for isotropic aggregates are Vp = 7.59(2) and Vs = 4.43(1) km/s, markedly lower than those of other principal minerals likely present in subducting slabs at upper mantle and transition zoneconditions. We used our results to calculate seismic velocities in typical dry and hydrated upper mantle and transition zone assemblages (Ohtani et al., 2004). Our results suggest that the presence of even small volume of phase E can reduce seismic wave velocities in isotropic aggregates, making phase E a plausible candidate to explain seismic velocity heterogeneities in subducting slabs. Future high-pressure and -temperature experiments should aim at quantifying the elasticity of phase E under mantle conditions.

Ohtani, Eiji, et al. "Water transport into the deep mantle and formation of a hydrous transition zone." *Phys. Earth Planet. Inter.* 143 (2014): 255-269.

Poster

## Determination of the structure of amorphous GeO2 up to 100 GPa by X-ray emission spectroscopy

**Georg Spiekermann[1], Max Wilke[1], Sylvain Petitgirard[2], Keith Gilmore[3], Manuel Harder[4], Christian Sternemann[5]**

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The application of valence-to-core X-ray emission spectroscopy (vtc-XES) to DAC experiments is a developing probe which allows insight into the structure of amorphous material.

The structure of compressed amorphous GeO2 above 40 GPa is uncertain, but of particular interest due to its similarity to SiO2, the main component of the Earth's mantle. A study of density measurements has postulated a density crossover of amorphous GeO2 relative to crystalline GeO2 phases (Hong et al. 2007). This would probably require an average Ge coordination number above six, which is the coordination in known stable GeO2 polymorphs at mantle pressures. A recent X-ray diffraction study reported an average Ge coordination number of seven at 60 GPa (Kono et al. 2016). This contrasts results of ab initio molecular dynamics, which postulate deviation of sixfold coordination not below 80 GPa (Du et al. 2017).

We compressed amorphous GeO2 up to 100 GPa in diamond anvil cells (DAC) and measured germanium valence-to-core X-ray emission spectra. Bethe-Salpeter spectral calculations of GeO2 polymorphs guide the interpretation of measured spectra.

Our results show that there is no necessity to invoke germanium coordination above sixfold to explain the observed spectra up to 100 GPa. Based on our observations, it is unlikely that compressed GeO2 glass exceeds the density of sixfold coordinated GeO2 polymorphs at the pressure conditions of the Earth's mantle.

# 4c) Dynamics of magmatic and volcanic processes

Talk

## Decompression induced phase separation of hydrous Vesuvius melt: vesicle nucleation or spinodal decomposition?

**Anja Allabar**, **Marcus Nowak**

*University of Tuebingen, Germany*

The phase separation of $H_2O$ fluids from supersaturated hydrous silicate melts drives explosive volcanism. The number of fluid vesicles per unit volume of silicate melt ($VND$) is a basic property that controls the efficiency of fluid-melt separation that controls the acceleration of magma ascent, and finally explosive volcanism. Continuous decompression experiments were performed at superliquidus temperatures to simulate decomposition of single phase hydrous silicate melts during ascent with AD79 Vesuvius white pumice composition. This pumice buried Herculaneum and Pompeii and is representative of other catastrophic phonolitic and trachytic explosive eruptions like the violent 39 ka Campi Flegrei and the 1815 AD Tambora eruption.

Experiments were conducted in an internally heated pressure vessel equipped with a high-pressure valve that facilitates continuous decompression. During equilibration at 200 MPa and 1523 K for 96 h, 5.3 wt% $H_2O$ were dissolved in the melts, equivalent to an $H_2O$ saturation pressure of 195 MPa. Subsequently, the hydrous melts were isothermally decompressed at 1323 or 1373 K with rates of 0.024-1.7 $MPa{\cdot}s^{-1}$. At final pressures ($P_{final}$) between 110 and 80 MPa, the samples were isobarically quenched within seconds. The $VND$ of the vitreous samples were determined with optical microscopy and quantitative backscattered electron image analysis using computational 2D to 3D transformation.

Homogeneously dispersed vesicles are observed in the samples decompressed to a $P_{final} \leq 100$ MPa. Thus, a high $H_2O$ supersaturation corresponding to a $\Delta P$ of 95 MPa is necessary to induce homogeneous phase separation. The samples show high $VND$´s of $10^5$ $mm^{-3}$, irrespective of decompression rate within the investigated range. Thus, even at a decompression rate of 0.024 $MPa{\cdot}s^{-1}$ the formation of vesicles with such high $VND$ inevitably causes efficient melt degassing coupled with rapid decrease in density within seconds due to short $H_2O$ diffusion distances on a 10 µm scale from the melt into fluid vesicles. This behavior has profound consequences for the degassing dynamics of natural polyphase hydrous magma because of the rapid increase of magma buoyancy required for explosive volcanism. Nucleation theory, which is commonly used to estimate magma ascent velocity during volcanic eruptions using $VND$ of volcanic ejecta, cannot be adapted to explain our experimentally determined decompression rate independent $VND$. Alternatively, decompression induced $H_2O$-silicate melt phase separation may be described by the theory of spinodal decomposition at the limit of thermodynamic stability.

Talk

## Dynamic magma-magma interface processes that moderate metal mass transfer in arc magma systems

**Adrian Fiege**[1], **Adam Simon**[2], **Philipp Ruprecht**[3], **Francois Holtz**[4]

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Mafic magma recharge of evolved crustal magma reservoirs is a common event that results in physical and chemical mixing processes. This magma-magma interaction drives compositional diversity through equilibration up to full hybridization, and can trigger volcanic eruptions. Rapid heat-flux commonly leads to the formation of a crystal-rich layer on the mafic side of the interface of juxtaposed (hotter) mafic and (colder) felsic magmas. Thus, diffusive mass-flux between the two systems may be controlled by crystal dissolution rates within the boundary layer and the formation of interconnected melt networks. In order to understand trace element signatures in volcanic deposits and their mafic enclaves, as well as in genetically related magmatic ore deposits, a rigorous experimental investigation of the involved dynamic processes is necessary. Here, the complex nature of magma-magma mixing requires a good understanding of both (1) major and trace element melt diffusivities, and (2) the role of crystal-rich layers at the interface. Thus, we performed super-liquidus (melt-melt) and sub-liquidus (magma-magma) diffusion-couple experiments at 150 MPa, 950-1100˚C, FMQ+1-FMQ+3. Hydrated, sulfur-bearing cylinders of dacite and basaltic andesite were equilibrated for up to 100 h.

The melt-melt experiments yielded similar melt diffusivities for V and W, while V and W diffusion is enhanced at FMQ+1 when compared to FMQ+3.

On the mafic side of the sub-liquidus diffusion-couple experiments, common mineral dissolution sequences were observed. The dissolution of the crystal-rich boundary layer scales as the square-root of time and, therefore, can be described as a diffusion-controlled process. This indicates that the rate at which mafic enclaves become completely assimilated in felsic magma depends on the efficiency of the removal of the emerging boundary layer. Thus, a cm-sized enclave would survive only ~1 year, if stirring and boundary layer removal is effective. Enclaves that survived for longer timespans in a magmatic system may indicate more sluggish convection.

Distinct redox pattern formed at the interface of the sub-liquidus experiments, perhaps as a result of diffusion-induced electron-hole imbalance [1]. Significant peaks in V, Zn, and W contents in the melt fraction near the interface may be directly related to this transient redox effect. We suggest that such kinetic effects may moderate magma-magma trace metal transfer, affecting geochemical signatures of magmas and their genetically related ore deposits. Further, redox and trace elements signature within and surrounding mafic enclaves may be used to understand their residence time prior to eruption.

[1] Fiege et al., 2017, GPL, 3.2, 190-198.

**Poster**

## Evolution and genesis of calc-alkaline magmas at the Paphsanias Volcanic Field, Aegean Arc

**Thomas Günther, Dominic Woelki, Bettina Storch, Christoph Beier, Karsten Haase**

*Friedrich-Alexander-Universität Nürnberg-Erlangen, Germany*

The Aegean arc is one of the arcs with the highest rate of sediment subduction and ~8 km of sediment are found in the Hellenic Trench. In 1984, the submarine Paphsanias Volcanic Field was discovered west of the islands of Methana and Aegina, the two major westernmost volcanic centers of the Aegean Arc. The Paphsanias Volcanic Field consists of six volcanic structures ranging from massive lava flows to relatively complex volcanic structures with heights of 300 m. These volcanic structures represent an early stage of submarine volcanism of the Aegean arc volcanoes. Four of the Paphsanias volcanic structures were sampled during the Pos512 cruise in 2017 and here we discuss the preliminary petrological and geochemical data of ~100 samples with basaltic to andesitic compositions.

The basis of two of the Paphsanias volcanic structures consist of basaltic lava flows with 10 to 7 wt.% MgO and 150 to 80 ppm Ni, whereas the shallower flows and lava domes have andesitic compositions. Here, we suggest that most andesites are generated by either fractional crystallization or magma mixing between mafic and silicic melts during replenishment of shallow crustal magma reservoirs. The Paphsanias basalts are more mafic than lavas from neighbouring Methana but also than known mafic lavas form other Aegean volcanoes. Iron and Ti contents of the Paphsanias and Methana lavas follow the same calc-alkaline trend. However, one of the submarine volcanoes shows V contents that overlap with the tholeiitic trend of lavas from Santorini which may reflect a change in state of redox of the Paphsanias Volcanic Field.

Compared to Santorini, ratios of Ba/Nb, Nb/Zr and Zr/Y are more enriched and probably indicate different degrees of partial melting, enrichment of the mantle source, and/or variable crust addition.

**Talk**

## Insights into the subsolidus cooling history of the Skaergaard Intrusion, Greenland – An application of diffusion chronometry

**Nicole Malz[1], Olivier Namur[2], Kathrin Faak[1]**

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The processes involved in the formation and cooling of large igneous bodies are not well understood. Although the *Skaergaard Intrusion* is probably the most studied layered mafic intrusion on Earth and has been in the focus of research for several decades, open questions remain regarding the processes of differentiation or the formation of igneous layering (e.g. *Holness et al., 2017*). Another important matter of debate concerns the cooling history of the intrusion both at supersolidus and subsdolidus stages. A better knowledge of cooling rates is however important to constrain the thermal structure and the thermal evolution of *Skaergaard*.

Application of diffusion chronometers on natural rock samples allows for a quantitative determination of subsolidus cooling rates. Here, we used the Mg-in-plagioclase and the Ca-in-olivine diffusion chronometers to map cooling rates in *Skaergaard*. Both diffusion chronometers are based on the extent to which temperature dependent ion exchange reactions proceed during cooling - in this case the diffusive exchange of Mg between plagioclase and clinopyroxene, and Ca between olivine and clinopyroxene, respectively. The use of two independently calibrated diffusion chronometers allows testing for the robustness of the derived cooling rates. We selected samples from different stratigraphic depths within the Layered Series of the *Skaergaard* intrusion that crystallized upwards on the floor of the magma chamber. Samples were also selected at variable distance from the vertical walls of the magma chamber. Our lateral and vertical selection of samples permits for rough estimates of the cooling history in three dimensions.

Different models for the cooling history for *Skaergaard* as a single batch intrusion (e.g. *McKenzie, 2011*) agree that cooling is expected to be fastest at the bottom of the intrusion (with magma crystallizing fast against cooler wall rock) and decrease towards the center. However, our preliminary results show a general trend from slower to faster cooling rates going from the base of the Layered Series to its top, indicating that the cooling history of the *Skaergaard* intrusion might be more complex than previously assumed.

Holness et al., 2017, Elements 13, 391-396

McKenzie, 2011, J. Petrol. 52, 905-930

Talk

## Melt fraction, distribution and interconnection determined by electrical conductivity and energy dispersive X-ray diffraction

**Georg Nover, Jutta von der Gönna**

*Universität Bonn, Germany*

This presentation deals with the in-situ detection of volume fractions of melt in labradortite and basalt at 0.3 GPa pressure and temperatures ranging from 400°-1500°C. Methods used were frequency dependent electrical conductivity (EC) and energy dispersive X-Ray diffraction (EDX). These techniques allowed melt-fraction determination under in-situ pressure and temperature conditions, while optical analysis (SEM) was performed on quenched samples. EC allowed to detect melt fractions as low as 0.03 due to changes in dielectric properties. Increasing melt fractions caused the formerly isolated melt bubbles to interconnect along grain boundaries, thus increasing the bulk conductivity. Electrical conductivity thus provides a measure for both, the formation of melt (dielectric property) and the degree of interconnection of melt (bulk conductivity). Energy dispersive X-ray diffraction experiments (EDX) provided an additional measure for the volume fraction of melt. EDX diffraction data were used to calculate the volume fraction of melt on the basis of the peak to background ratio. In a final step the experimental data (SEM, EC, EDX) were compared with geometric models of melt distribution, namely the Archie-, cube-, tube-, Hashin-Shtrikman $HS^+$ and $HS^-$ model. The electrical 'polarizability' data closely fit the $HS^+$ model, while bulk-conductivity data were found to be less sensitive for melt fraction detection.

Talk

## Non-isothermal diffusive analysis: experimental validation and application to sanidine megacrysts from Taapaca volcano (Nothern Chile)

**Smruti Sourav Rout, Burkhard C. Schmidt, Gerhard Wörner**

*GZG, Georg-August-Universität Göttingen, Germany*

Diffusion chronometry on zoned crystals allows constraining duration of magmatic evolution and storage of crystals once temperatures are precisely known. However, non-isothermal diffusion is the rule in natural samples and thus, time-scales cannot be determined with confidence while assuming isothermal conditions. Therefore, we experimentally test the "Non-isothermal Diffusion Incremental Step (NIDIS) model" (Petrone et al. 2016) and after validation apply it to compositionally zoned sanidine megacrysts in the dacites from Taapaca volcano (N-Chile).

For the experiments, we used Cl and F as fast-diffusing elements in anhydrous homogenous glass of Montana Blanca phonolite composition. The experimental set-up successively creates multiple diffusive interfaces by adding glass blocks of different Cl and F concentrations and continues diffusion experiments at a different temperature. The compound series of diffusion interfaces represents distinct compositional zones that diffusively interact at different temperatures. The starting temperature ranged from 975 to 1150 $^0$C and each set of experiments included a temperature change of 85-150 $^0$C at 1 kbar pressure and a total duration of 8-12 hours. The Cl and F concentration profiles were analysed and estimated diffusion times from the NIDIS-model matched well with actual values.

The NIDIS-model was applied to multiple growth zones in the sanidines of dacite samples from Taapaca volcano. We observe sharp jumps in Ba concentration each corresponding to resorption interfaces that reflect distinct heating events. Thus different growth zones formed at different temperatures. Amphibole-plagioclase thermometry gave temperatures of ~700-800 $^0$C and Al-in-Hornblende barometry gave pressures of 1-3 kbar for each growth zone separately. Ba-profiles from quantitative analyses and element maps were modelled to obtain diffusion times for individual diffusive boundaries. Diffusion times ranged from 1 to 50 ky adding up to total residence timescales of 30 to 470 ky for different crystals from different stages of eruption. A comparison of the variation in temperature against Ba-content across the crystals, and the magnitude of individual diffusion timescales suggest a typical trend where the crystals remained in a rhyodacite melt at near eutectic composition for thousands of years at shallow depth. Frequent recharge by mafic magmas kept the system thermally alive and caused multiple heating and resorption events within the crystals. The magmatic system started to heat and speed up only ~1-3 ky before the eruptions that brought the crystals to the surface.

Reference:Petrone CM et al. (2016) Pre-eruptive magmatic processes re-timed using a non-isothermal approach to magma chamber dynamics. Nat. Commun. 7, 12946 doi:10.1038/ncomms12946.

Poster

## Tectono-magmatic evolution of Paka volcano, northern Kenya Rift: new insights from magma chemistry and systematic Ar/Ar dating

**Masafumi Sudo[1], Manfred R. Strecker[1], Kai Hahne[2], Simon Riedl[1], Tito Lopeyok[3], Geoffrey Mibei[3]**

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The tectonically active Kenya Rift is an integral part of the magmatic eastern branch of the East African Rift System. The volcano-tectonic axis of the Kenya Rift is located in an actively deforming, approximately 40-km-wide sector that contains Quaternary volcanic

edifices that connected via zones of closely spaced normal faults. North of the equator, the Kenya Rift hosts 6 caldera volcanoes that have been repeatedly active since mid-Pleistocene time. However, the exact timing of magmatic activity and the relationship between extensional tectonism and magmatic activity is only known to first order. Mt. Paka located at 00˚55'N, 36˚12'E, a shield-volcano edifice with predominately trachytic composition, belongs to these rift volcanoes. Here we report on systematic $^{40}Ar/^{39}Ar$ dating of 32 rock samples from basaltic and trachytic lava flows to constrain the regional volcano-tectonic evolution.

Volcanic activity at Paka began at 0.58 Ma with the eruption of the nepheline-normative basalts; hypersthene-normative basalts that are widely in the greater Paka region, erupted between 0.3 and 0.1 Ma during an episode with predominatley trachytic eruptions that started at about 0.43 Ma. Overall, magmatic activity was sustained between 0.58 and 0.012 Ma. However, we recognized the existence of three pronounced eruptive periods during this interval: 0.6-0.35 Ma (I), 0.35-0.1 Ma (II) and 0.1-0 Ma (III). During the evolution of the volcanic complex the spatial evolution of eruptive vents shows a gradual development toward a NNE-SSW orientation, which is parallel to the trend of the Kenya Rift.

Our new spatiotemporal assessment of magmatic and tectonic activity and the evolution of the geochemical characteristics of Paka volcano suggest that the magmatism is closely related with diapiric mantle upwelling. Accordingly, the diapir separates smaller batches of nepheline-normative basaltic magmas under higher-pressure conditions than those of more voluminous hypersthene-normative basaltic magmas at shallower depth with a higher degree of melting. Nb/Zr ratios in the rocks of the three different eruptive episodes gradually decrease, possibly reflecting repeated segregation of basaltic magmas by fractional melting. This may indicate an original mantle-diapir source and subsequent differentiation toward trachytic compositions, because the partitioning coefficients of Zr against mantle minerals are slightly higher than those of Nb. Taken together, our results suggest that the trachytic and nepheline- and hypersthene-normative basaltic trends in the Paka volcanics may represent a single magmatic plumbing system for this rift volcano, where magma genesis was intimately associated with extensional tectonic activity along the volcano-tectonic axis of the Kenya Rift.

**Poster**

## The Shatsky Rise volcanic plumbing system: magma transport dynamics and storage conditions recorded by a crystal mush.

**Thomas Daniel van Gerve[1], David Neave[1], Olivier Namur[2], Francois Holtz[1], Renat Almeev[1]**

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In recent years our understanding of sub-volcanic magmatic systems has shifted away from models of large-scale, long-lived, liquid-dominated magma chambers towards one where melt is distributed between crystals in crystal+liquid mushes. In this case, melt exists mainly as small pockets within a framework dominated by crystals. In such systems, magma bodies are transient features created by rearrangement within the crystal mush.

During melt migration from deep magma chambers towards Earth's surface, minerals may experience vertical transport and storage at different levels. Crystals can also grow compositionally distinct zones in each different magmatic environment. By doing this they effectively record the internal dynamics and the architecture of plumbing systems beneath volcanoes. Detailed, thin-section scale investigation of crystal textures and compositional zoning is therefore extremely useful for understanding large-scale magmatic processes. In this study, we investigate trans-crustal melt transport and the conditions of magma storage beneath Shatsky Rise (northern Pacific Ocean), a large igneous province which formed an oceanic plateau in the early Cretaceous. We chose this study area because Shatsky Rise erupted typical mid-ocean ridge basalts through a comparatively thick oceanic crust.

Plagioclase shows strong zoning and its plateau compositions and zoning patterns indicate three at least main magmatic environments in which crystallization took place. They are characterized by distinct anorthite (An; Ca/(Ca+Na)) contents of >78%, 70-78% and <70% An. Plagioclases from the different environments have specific degrees of rare earth and incompatible trace element enrichment, with concentrations increasing with decreasing anorthite content.

Systematics in the sequence of growth zones are interpreted to reflect transport pathways between magmatic environments. Sequential transport to the next lowest An environment is common, suggesting upwards migration into increasingly evolved melts. Direct transport from the most primitive to the most evolved environment is also well established. This demonstrates that trans-crustal magma transport takes place along multiple different routes.

Additionally, complex dissolution and re-precipitation textures in high anorthite zones indicate repeated injection of liquids not in equilibrium with the crystal mush.

This study of mineral populations and compositional zoning highlights the transient and dynamic nature of crystal mushes and can ultimately be used to construct models for volcanic plumbing systems (e.g. depth and temperature of magma storage regions) and their temporal evolution.

# Topic 5: Sedimentary systems

## 5a) Temperature and fluid dynamics in sedimentary basins

Talk

### Terrestrial heat flow in basin modelling: new findings for the North German Basin

**Sven Fuchs, Andrea Förster**

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Knowledge of the subsurface temperature field is paramount in the exploration of resources, such as hydrocarbons and geothermal energy. The terrestrial heat flow representing the conductive thermal field is a crucial parameter in such a characterization. It is determined from measured borehole temperature (temperature gradient) and rock thermal conductivity (TC). In situations of no drill core availability, TC needs to be determined indirectly. We have developed a well-log based approach to arrive with TC predictions for clastic rocks, carbonates and evaporites. The prediction equation describe interrelations between standard well-log data (bulk density, natural gamma-ray, sonic interval transit time, hydrogen index, photoelectric factor, and petrophysical descriptors determined from these) and rock thermal properties as derived from a 'synthetic data set' of global nature. Thus TC predictions can be made of good quality requiring no knowledge of the rock mineral composition or details of lithotypes in borehole. The application of such a well-log based approach to data of the GeneSys borehole at Hannover resulted in a complete TC profile to 3800 m depth, which was validated by TC laboratory data. Using the TC profile and measured temperature log data, heat-flow density was calculated along an entire borehole section. With this approach a reduction of heat flow of up to 25 mW/m² was observed in the upper kilometer of the borehole. The general alignment between interval temperature gradients and lithology (and hence TC) allows to exclude fluid-driven heat transport responsible for this reduction. Given this fact, the observation is as a clear evidence for the paleo-climate impact on the subsurface temperature by last glacial periods. The finding calls for critical evaluation of former heat-flow data in terms of depth realm of determination before they are used in basin modeling. The undisturbed surface heat flow at the Hannover site of about 85 mW/m² is within the range of new values (68–91 mW/m²) for the eastern part of the NGB, determined at depths not afflicted by paleoclimate. The new values, being much higher than those previously reported for the basin, will alter temperature predictions from basin modeling. Thus, a thorough underpinning of the data for the NGB by further studies is warranted.

Poster

### Stress-dependence of the total gas storage capacity of carbonaceous shales

**Garri Gaus, Reinhard Fink, Bernhard Martin Krooss, Ralf Littke**

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Gas storage capacity (GSC) is the maximum amount of gas that can be accommodated in a gas shale (in the free and adsorbed state) under reservoir temperature and pressure conditions. It is a key parameter in the appraisal of the economic feasibility of a shale gas play and involves the assessment of the storage volume (porosity, specific pore volume) and excess sorption isotherms. Most porosity determinations are still nowadays conducted on "unstressed" samples (e.g. by He-pycnometry, immersion techniques, optical methods, low-pressure nitrogen adsorption or small-angle neutron scattering) without taking into account the effect of *in situ* overburden stress on porosity. Similarly, adsorption isotherms are still mostly determined on powdered samples, thus ignoring the effect of rock fabric and overburden load on adsorption capacity.

In the present study the stress-dependence of the free and adsorbed methane storage capacity was determined on dry intact cores from the Eagle Ford (EF), Alum (AL) and Kimmeridge (KI) formations under controlled confining stress up to 40 MPa. The results indicate that overburden stress reduces both, the free and the adsorbed gas storage capacity of shales.

Based on the laboratory results free and adsorbed gas storage capacities were calculated for the three shales at a depth of 2500 m assuming a 30 °C geothermal gradient, a 25 MPa/Km lithostatic stress gradient and a 10 MPa/Km pore pressure gradient. The volumetric (free gas) storage capacities under these conditions amount to 1280 (EF), 1049 (AL) and 595 (KI) mol $CH_4$/m³, respectively. The corresponding sorptive storage capacities were 115 (EF), 286 (AL) and 642 (KI) mol $CH_4$/m³.

Stress-dependence of the free gas capacity decreased in the order KI >> EF > AL, whereas that of adsorbed gas capacity decreased in the order of EF > KI > AL. The experimental data suggest that disregarding stress-dependence will lead to an overestimation of the total storage capacity of 7% for the AL, 13% for the EF and 25% for the KI at 2500 m depth. Stress sensitivity coefficients of free gas capacity (-0.008, -0.002 and -0.001 $MPa^{-1}$) and adsorbed gas capacity (-0.005, -0.02 and -0.004 $MPa^{-1}$) differ and do not follow the same trend for this sample set. This indicates that, while reduction of free gas capacity is controlled by poroelastic compression, the reduction of adsorbed gas capacity is likely to reflect a more complex mechanism including poroelastic compression and adsorption-induced swelling.

Talk

## Organic-rich intervals of Late Mesozoic to Cenozoic age in the on- and offshore area of Cyprus and their impact on petroleum systems in the Eastern Mediterranean Sea

**Sebastian Grohmann**[1,2,3], **Maria Fernanda Romero-Sarmiento**[2], **Fadi Henri Nader**[2], **Francois Baudin**[3], **Ralf Littke**[1]

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During the last decade, significant biogenic gas discoveries have rendered the Eastern Mediterranean Sea and especially the Levant Basin to one of the world's most promising exploration frontier areas. For the assessment of petroleum systems, detailed knowledge about potential source rocks is required and can help to reduce the risks in exploration. While a lot of work has been performed on potential source rocks along the eastern and southern margin of the Levant Basin, its western margin is still underexplored. Therefore, in this contribution, we present new geochemical and petrographical data of organic-rich rocks of Late Mesozoic to Cenozoic age from the on- and offshore area of Cyprus and discuss their implication for petroleum systems in the area.

The results prove the existence of organic OM-rich intervals in the on- and offshore area of Cyprus. The OM in the analyzed samples comprises marine oil-prone type II kerogen with HI values between 100 and 600 mg HC/g TOC. With TOC contents up to 5 wt.% many of these samples show good source rock properties. However, all samples are of immature state. Nevertheless, the recent hydrocarbon discoveries in the Eastern Mediterranean Sea such as the giant field Zohr comprise mainly natural gas of biogenic origin. Biogenic gas production occurs at shallow burial depths and low temperatures, thus even these immature source rocks might contribute to HC production.

The enrichment of TS contents in the onshore Upper Miocene samples indicates a deposition under anoxic conditions, which is in accordance with the idea of several anoxic silled sub-basins around the island of Cyprus during the Miocene.

For the offshore intervals, TS/TOC as well as Pr/n-C17 vs Ph/n-C18 ratios indicate dysoxic conditions during deposition, which might be the result of temporarily active upwelling systems, implying that deposition and preservation of OM was likely restricted to the closer surrounding of the ESM. However, since the Mid Eocene the Eastern Mediterranean Basin was successively cut off from the Indian ocean to the east due to the subduction of Afro-Arabia below Eurasia, which might have favored the evolution of anoxic bottom waters in the Levant Basin. Thus, OM might have been redeposited by mass flow transport (e.g. turbidites) towards the deeper parts of the basin, where it was preserved under anoxic conditions and buried deep enough to reach thermal maturity.

The presence of such deep buried source rocks is indicated by the observation of solid bitumen in Lower Eocene sections.

Poster

## Porenraumparameter von Sandsteinen und spektrale induzierte Polarisation (SIP): Abhängigkeit des komplexen elektrischen Widerstands vom hydrostatischen Druck und chemischer Beeinflussung durch superkritisches $CO_2$ ($scCO_2$)

**Nasser Hbib**, **Arne Mansfeld**, **Georg Nover**

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Transportparameter von Gesteinen lassen sich mit der Methode der Spektralen Induzierten Polarisation (SIP) ableiten, allerdings sind die zugrunde liegenden Polarisationsmechanismen bisher nicht vollständig verstanden. Eine Weiterentwicklung gängiger Modellvorstellungen kann dadurch erreicht werden, dass a) SIP-Messungen an Sandsteinproben, deren Porenraum durch unterschiedliche hydrostatische Drucke, oder b) durch chemische Prozesse wie scCO2 verändert wird, durchgeführt werden. Änderungen der Polarisation können somit mit der druckabhängigen Permeabilität, der Porosität und der inneren Oberfläche des Porensystems (BET) korreliert werden. Weiterführende Erkenntnisse über den Zusammenhang zwischen der Struktur des Porenraumes und frequenzabhängigen, komplexen SIP-Daten sind somit möglich.

Poster

## Understanding rock properties from basin to reservoir scale – Examples from eastern North German Basin

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The Central European Basin is considered to feature prominent potential for subsurface use, not only regarding conventional oil and gas exploration but also for non-conventional energy usage including geothermal energy or storage of fluids and natural gases for carbon capture and other geological storage application. For all of these applications questions concerning petrophysical parameters like porosity, permeability and temperature distribution of potential reservoir units on a regional scale is of uttermost importance. Conventional basin modelling techniques can be used to study the thermal and structural evolution and to determine these parameters.

On a regional scale petrophysical parameters were calculated on eight boreholes comprising Mesozoic Formations of the eastern North German Basin by using 1D basin modelling performed with PetroMod software (vers. 14). Standard input parameters as lithologies and their properties, ages for stratigraphic horizons as well as periods of non-deposition and erosion have been used from borehole descriptions.

Additionally, matrix porosity and fluid content were determined on a reservoir scale based on geophysical borehole measurements by using ELAN software by Schlumberger. As a result, reservoir characteristics for two the different stratigraphic reservoirs could be determined for the Lower Triassic and the Jurassic. The investigated area was affected by several uplift and erosional events during the Mesozoic and Cenozoic with different regional effects. Burial anomalies have been observed within the boreholes in the northern part and in the southern central part of the study area. Those boreholes show higher porosities than the others without such an anomaly. Detailed reservoir modelling reveal a higher vertical resolution of reservoir units and intercalations of shale layers. For the Jurassic reservoir units reservoir modelling show generally loser porosity values than basin modelling.

For a regional understanding of rock properties and lateral distribution of porosity and temperature further dissemination from 1D into the 3D domain is needed. However, correlation between the boreholes with known parameters for 1D modelling is the first step. Basin and reservoir modelling can serve as method to approximate regional and local petrophysical rock properties as first estimation if measured values are not available.

Talk

## Salt Tectonics in Oman – multi-scale and integrated outcrop and subsurface studies of salt deformation mechanisms

**Peter A. Kukla**[1], **Janos L. Urai**[2], **Lars Reuning**[1], **Stephan Becker**[1], **Shiyuan Li**[3]

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In the late Neoproterozoic to Early Cambrian Ara Group of the South Oman Salt Basin (SOSB), differential loading of thick continental clastics above evaporites and interbedded carbonates led to the formation of a complexly folded salt sequence. It comprises bedded salt and salt diapirs and includes hydrostatically pressured or highly overpressured intra-salt carbonate 'stringers' which form a self-sourcing petroleum system. Six surface-piercing salt domes in the Ghaba Salt Basin (GSB) of northern Interior Oman provide the unique opportunity to study the structural geology, diagenesis and geochemistry of intra-salt carbonates which are time equivalent with the deeply buried evaporites and intra-salt carbonates in the SOSB.

Multi-scale and integrated studies in both basin systems were based on seismic, borehole data and field work and included petrography, (isotope) geochemistry and numerical modelling, striving towards a better understanding of the controlling factors of salt tectonic deformation mechanisms. In the SOSB, the Ara Sequence was deposited in six cycles, comprising carbonates and evaporites which have subsequently been buried to a depth of 3 to 6 km and which underwent a complex diagenetic evolution, with various stages of cementation in shallow (early) and deep (late) burial environments. During the burial process, the sedimentary geometries in the Ara Group were strongly influenced by syn-sedimentary salt tectonics and the early formation of overpressures. Structural, petrophysical and seismic data analysis suggests that overpressure generation is driven by fast burial of the stringers in salt, with a significant contribution by thermal fluid effects and kerogen conversion. Hydrocarbon-impregnated black rock salt suggests that it must have repeatedly lost and then regained its sealing capacity.

Microstructures indicate dislocation creep and fluid-assisted grain boundary migration as the main deformation mechanisms operating in the deep subsurface. Different stylolite generations in the stringer intervals have either formed by the weight of the overburden or by bending stresses during stringer deformation. Finite element models suggest that stylolite growth started already prior or in initial stages of salt tectonics and most likely continue until recent times. Another key result suggests that breakouts and drilling induced/enhanced fractures mapped within the stringers represent a present-day, non-hydrostatic in-situ stress field with radial orientation. The vertical distribution of these features as well as the Finite Element Modelling imply that the recent in-situ stress field is caused by slow gravitational sinking of the stringers with a total vertical displacement of up to ~ 100 m (0.2 m/Ma) since early Ordovician times.

Talk

## The Jurassic in the German Central Graben and its potential as a thermogenic source for shallow gas accumulations

**Simon Müller**, **Jashar Arfai**, **Fabian Jähne-Klingberg**, **Frithjof Bense**

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Within the German Central Graben, the source of shallow gas accumulations in Plio-Pleistocene sediments is still unknown. However, a proportion of thermogenic gas from a deeper source is assumed due to various indications. Geochemical data of the shallow gas field B17 in the Dutch Central Graben are suggestive to a significant thermogenic contribution. The occurrence of gas chimneys on reflection seismic data underneath the shallow gas accumulations indicate fluid migration from a greater depth. Also, the geographically limited appearance of the shallow gas accumulations to the Jurassic graben system may point to formations as a source that were deposited or are preserved only in this area. The purpose of this study is to assess the potential of source rocks in the German Central Graben and to identify the most probable sources of a thermogenic contribution to the shallow gas accumulations. For this reason, prominent source rocks of the Southern North Sea (the Clay Deep Member and the Posidonia Shale Formation) were mapped anew. These and other potential formations from the Upper Triassic to the Lower Cretaceous were integrated into an existing petroleum system model of the Northern German North Sea, which was modified for the new requirements. Results from the petroleum system modeling indicate Middle to Upper Jurassic coal measures of the Central Graben Subgroup as well as Lower Jurassic Aalburg and Sleen Formation as potential sources for thermogenic methane within the shallow gas accumulations of the German Central Graben.

Talk

## Burial history and sandstone diagenesis: the example of Schilfsandstein (Triassic) in the North German Basin (Usedom area)

**Sebastian Niegel**[1], **Matthias Franz**[1], **Graciela M. Sosa**[1], **Markus Wolfgramm**[2]

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The North German Basin yields enormous geothermal resources bound to Paleozoic petrothermal and Mesozoic hydrothermal reservoirs. Ongoing research on Mesozoic sandstone reservoirs attempts at an exploration strategy contributing to improved predictions of hydrothermal reservoirs, in particular of reservoir qualities. The case study on the mid-Carnian Stuttgart Formation (Schilfsandstein) in the Usedom area (NE Germany) exemplifies the control of burial history on the diagenetic evolution of sandstone reservoirs. For the Usedom area, previous studies on the maturity of carbonaceous Palaeozoic and Mesozoic strata resulted in maximum burial depth largely in agreement with present-day burial depths of these strata. In contrast, the present-day burial depth of the Schilfsandstein in the range of 700–1000 m appears not in agreement with its diagenetic history as corrosion of detrital grains, authigenic overgrowth and cementation of open intergranular pore space evidences substantial burial diagenesis. An integrated study combining classical microscopic methods with cathodoluminescent microscopy, SEM-EDX, fluid inclusions, isotopic analysis, and X-ray diffraction of bulk rock samples enables to reconstruct the diagenetic succession from eo-diagenetic to late diagenetic stages. Accordingly, eo-diagentic pyrite and pore-filling marine carbonate cements were followed by formation of early diagenetic tangential illite. In particular pore-filling marine carbonate cements supported the grain fabric during burial resulting in low to intermediate grain packaging. During later diagenetic stages, marine carbonate cements were resolved and replaced by overgrowth of quartz and K-feldspar on detrital grains and formation of pore-filling kaoilinite, chlorite and analcime. The diagenetic succession ends with pore-filling euhedral dolomite crystals and blocky dolomite. Experimental studies have shown that corrosion and dissolution of quartz, illite and K-feldspar and precipitation of analcime and chlorite require fluid temperatures above 60° C. In accordance to this, primary aqueous inclusions trapped in late diagenetic carbonate, i.e. iron-rich dolomite, indicate brine compositions between 81–94 % $H_2O$, 5–15 % $CaCl_2$ and 1–4 % NaCl and minimal fluid trapping conditions in the range of 86–137° C. Considering these results and assuming a Mesozoic geothermal gradient of 3,9 K/100 m a minimum burial depth of 2000 m is suggested for the Schilfsandstein in the Usedom area. This calls for a revised history for this part of the North German Basin which either involves greater burial depth followed by exhumation and/or strongly increased values of heat flow.

Poster

## Changes of petrophysical properties of sandstones due to interaction with supercritical carbon dioxide

**Georg Nover**, **Stephanie Heikamp, Jutta von der Gönna**

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Within the framework of the BMBF-funded COMICOR project, sandstones from the Hessian Depression have been studied for changes in petrophysical and petrological porperties causes by interaction of the sandstone with supercritical $CO_2$ ($scCO_2$). The sandstones acted as model substances for the underground storage of industrial $CO_2$ separated from flue-gases. Axial and radial oriented plugs, in regard to the borehole axis, have been used in this study. Flow conditions were measured in horizontal and vertical direction. Petrophysical and petrological properties of the plug-samples were measured on untreated and $scCO_2$-altered samples. The $scCO_2$-experiments were performed in an autoclave under the pressure and temperature conditions (p >12 MPa; T > 120°C) of a deep-seated saline aquifer. The qualitative and quantitative mineralogical composition was determined by x-ray powder diffraction (XRD) and Rietveld refinement, while the chemical composition was determined by x-ray fluorescence analysis (XRF). No changes in the mineral composition could be detected with XRD after the autoclave experiments, however, XRF reveald the mobilization of calcium and aluminium.ICP-OES-MS measurement of autoclave fluids confirmed these findings.

Partial dissolution of feldspar and clay minerals was detected by means of scanning electron microscope (SEM) imaging. The porosity of the samples did not change significantly even after reaction times greater than four month. In contrast the permeability showed a time dependent increase that was different for the two experimental setups chosen. If the pore volume of the samples was fully saturated with artificial brine (3 M NaCl-solution and $scCO_2$) the increase was less than one order in magnitude, whereas partially saturated samples showed an increase of up to three orders in magnitude. In the latter case the $scCO_2$ could directly interact via the electrochemical double layer with the rock forming minerals. As the hydraulic and the electrical charge transport are related to the same pore-system, an increase in permeability should correlate with an increase in conductivity. This was confirmed by means of impedance spectroscopy (IS) performed in the frequency range from 600 Hz up to 120 kHz, and independently by spectral induced polarization (SIP) measured in the frequency range from mHz up to kHz.

**Talk**

## Application of crustal thickness inversion for thermal history modeling in the Gippsland Basin, Victoria, Southeastern Australia

**Joschka Röth[1], Adeline Parent[2], Cassandra Warren[2], Daniel Palmowski[2], Ralf Littke[1]**

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The Gippsland Basin represents a reactivated aulacogen, which is oriented perpendicular to the shelf breakoff at the southeastern edge of the Australian continental margin between Victoria and Tasmania. A typical synrift sequence followed by tectonic inversion and a series of superimposing extensional and compressional episodes related to the opening of the Southern Ocean and the Tasman Sea enabled the formation of the prolific Latrobe petroleum system within the stratigraphic successions.

This study aimed for improved understanding of the relationship between the crustal evolution and the thermal history of the Gippsland Basin, which have implications for burial history and the timing of the petroleum system. The applied workflow included the setting up of a new 3D basin model, seismic interpretation of major faults and magmatic features, interpretation of the main stratigraphic boundaries, and the update of the basement topography. The new input was used to run multiple scenarios for crustal thickness inversion and subsequent basal heat flow modeling. The resulting stretching maps of crust and mantle and corresponding heat flow trends were used to calibrate the model. Finally, a crustal layer model was assigned, and the new 3D basin model was simulated.

Model results show that the Early Cretaceous initial breakup was accompanied by increasing basal heat flow from originally 50 $mW/m^2$ to a maximum of approximately 90 $mW/m^2$ in the basin center. Subsequent episodes of inversion and thermal subsidence resulted in fast cooling during the Late Cretaceous and continuous (slower) cooling (45 to 50 $mW/m^2$) since the Paleogene. Late Cretaceous magmatism locally increased the heat flow and generated a set of intrusions and volcanic layers along the northern basin margin.

Starting with a calibrated prerift lithospheric thickness of 65 km (continental crust = 25 km; upper mantle = 40 km), the boundary between the lithosphere and the asthenosphere (1333 °C isotherm) was temporarily elevated to shallow levels of about 40 km. The brittle crust was stretched to present-day crustal thicknesses ranging from 8 to 18 km and depth-to-Moho was decreased to only 15 to 25 km. The cooling and thickening of the upper mantle after rifting resulted in a present-day lithospheric thickness of approximately 80 km.

The direct influence of the Mid-Cretaceous rifting-associated thermal peak on kerogen maturation seems to be restricted to the Early Cretaceous Strzelecki Group, whereas the Late Cretaceous source rocks reached their thermal maximum and highest maturity only at present day.

# 5b) Advanced techniques and case studies in sedimentary provenance analysis

Talk

### High-precision measurement of δ17O and δ18O in cap carbonates and their siliciclastic component

**Nina Albrecht**[1], **Andreas Pack**[1], **Mark Thiemens**[2], **Xiaolin Zhang**[3], **Yunpei Gao**[3], **Yanan Shen**[3]

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Neoproterozoic cap carbonates formed in the immediate aftermath of a global glaciation event ("Snowball Earth") [1]. Accumulation of atmospheric CO2 during the glaciation led to higher erosion rates, higher Ca input into the oceans and cap carbonate precipitation [2]. Cap carbonates are typically thinly laminated and contain varying amounts of siliceous material [2]. Carbonate δ18OVPDB of consistently lower than -6 ‰ likely reflect precipitation from a mixture of seawater and isotopically light meltwater [2, 3].

By analyzing the triple oxygen isotope composition of the host carbonate along with the cherty material, we aim to shed light on the formation and diagenetic alteration conditions of Ediacaran Doushantuo cap carbonates from South China. High-precision triple oxygen isotope analyses of the carbonate will be conducted with a newly developed protocol including high-resolution gas source mass spectrometry using a Thermo 253 Ultra mass spectrometer. The silicate fraction will be analyzed by laser fluorination as described previously [4].

[1] Hoffman et al. (1998) Science 281 (5381), 1342-1346.
[2] Shields (2005) Terra Nova 17, 299-310.
[3] Wang et al. (2008) Geology 36 (5), 347-350.
[4] Pack et al. (2016) Rapid Commun Mass Sp 30, 1495-1504.

Talk

### What can we learn from the first interlaboratory round robin test for heavy mineral analysis?

**István Dunkl**[1], **Hilmar von Eynatten**[1], **Keno Lünsdorf**[1], **Sergio Andò**[2], **Andrew C. Morton**[3]

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Similar to the standardization efforts performed regularly in technical and chemical research some branches of analytical geosciences have conducted interlaboratory comparisons by circulating either well certified or well homogenized standard samples. The daily work would be impossible without these certified natural reference materials regarding methods such as U-Pb, K-Ar, fission track and helium geochronology, coal petrography and illite "crystallinity" or many geochemical analytical techniques.

In the field of sediment provenance studies heavy mineral analysis plays a prominent role. It got even wider perspectives recently, as advanced spectroscopic techniques, e.g., Raman, and automated procedures allow for generating much higher numbers of observations than the classical technique based on polarizing microscopy. In this way the statistical robustness of the HM proportions and HM ratios can achieve significant improvements. However, automated procedures may suffer from distinct shortcomings and a systematic comparison of different laboratories and different techniques have not been performed so far.

We organized a round robin test and distributed two different heavy mineral concentrates to over forty laboratories. The goals of the interlaboratory test are (i) to outline the reproducibility and comparability of heavy mineral analyses, and (ii) compare the different techniques. We did not use natural HM samples in order to avoid the influence of polyphase (composite) grains, which may be treated differently by the users and thus introduce some subjectivity to the measurements. Instead, the mixtures were made from high purity monomineralic components, mostly from crushed monocrystals. In order to mimic the usual appearance of the detrital grains air abrasion was applied on most of the monomineralic samples to produce more-or-less rounded grains. The heavy mineral concentrates were sieved to 63-125 µm size fraction. The different monomineralic components were mixed with gravimetric control.

The participants were asked to apply their usual techniques to the test samples, report their procedure, the degree of experience of the observer, the heavy mineral counts and, separately, opaque, lithic fragments and unidentified grains. The results will be presented anonymously, and for the first time at the Dublin WGSG meeting.

Talk

### Zircons to the front: a 80 Ma record of foreland sedimentation in the Rheno-Hercynian Variscides

**Wolfgang Franke**[1], **Hermann Huckriede**[2], **Martin Salamon**[3], **Volker Wrede**[3]

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Detrital zircons from late Devonian to Stephanian flysch and molasse sediments, combined with detrital mica ages, permit to reconstruct accretion and exhumation along the Rheno-Hercynian (RH) active margin.

Late Devonian greywacke turbidites record erosion of a north-Armorican upper plate (Franconia, eroded), with Late Neoproterozoic (Cadomian) arc magmatism, Cambro-Ordovician rift magmatism, Silurian/Early Devonian magmatic arc rocks relating to southward subduction of the Rheic ocean, but also mid/late Devonian granitoids formed during southwards subduction of the RH ocean. In the same beds, detrital glaucophane and muscovites with high Si/Al ratios document subduction-related metamorphism at the tectonic front. Granitoids and MP/HP micas represent a paired metamorphic belt during incipient RH subduction All the above components persist into the latest Westphalian or even Stephanian. Up-section, zircons reveal a ± continuous shift of felsic magmatism towards younger ages, from 380-360 (in the Late Devonian) to 320-300 Ma (Westphalian C-D and Stephanian). While the older grains can be assigned to diachronous collisional magmatism, the youngest zircons already herald the Permian magmatic flare.

During the Namurian A, sedimentary petrography and clast analysis reveals a rapid change from dominant magmatic rocks toward meta-arenites, and zircons prove that those arenites have Mesoproterozoic Baltic sources. Ductile deformation and metamorphic grade of arenite clasts document accretion to and exhumation from the base of the orogenic wedge. Those zircons transported "back to sender" persist into the Stephanian. Their source must be sought in Devonian sandstones equivalent to the Taunus quartzite presently encountered in the Spessart and Ruhla segments of the Mid-German Crystalline High (MGCH) but in tectonic units eroded from above its present-day erosion level. Unroofing of rocks now seen in surface outcrops of the MGCH is indicated by mica cooling ages of 328-315 Ma in Westphalian C and D sandstones.

Sedimentary petrography, zircon and mica studies, combined with estimated volumes of synorogenic sediments and of recycled material permit to deduce that ≥ 90 km of the RH distal passive margin were lost by accretion and recycling, which adds to tectonic balancing and enlarges the width of the passive margin (today 240 km) to originally ≥ 670 km.

**Poster**

## High-resolution sedimentological and geochemical investigations of the Leutesdorf Formation, Mayen, Germany

**<u>Edouard Grigowski</u>**

*University of Bonn, Germany*

There is ongoing discussion on the stratigraphic and depositional relationship of the *Hunsrückschiefer*, known worldwide for its well-preserved fossils, and the slates of the Mayen region, which contains equally well-preserved fossils as well as being the Mid-European economic centre for the high-quality roofing slate industry. While the *Hunsrückschiefer* is well understood in terms of its palaeontological, tectonic and sedimentological history, the same cannot be said for the *Moselschiefer*. The aim of this study is to provide a better understanding of the depositional conditions of the *Moselschiefer,* comparing and contrasting it with the *Hunsrückschiefer.* A high-resolution 24.29 m log was measured and sampled from the Leutesdorf Formation in the Katzenberg mine, near Mayen, with additional sampling from the Kaub Formation in the Herrenberg mine, near Bundenbach. The depositional conditions were analysed using facies analysis, supported by geochemical proxies, which evidenced small-scale changes within the succession. Provenance analysis indicates a mixed felsic/mafic source for all of the samples while the presence of framboids and other spheroids, determined by REM analysis, suggests a fluctuating redox boundary within the sediment. The results of this study would indicate that the Early Devonian-age sediments of the Leutesdorf Formation were deposited in a low-energy setting along the active continental margin of southern Laurussia. Although lithologically similar, the detailed sedimentology and geochemistry of the studied samples would suggest that the *Moselschiefer* and *Hunsrückschiefer* need to be regarded as two separate units, whose precise relationship with one another is not altogether clear. It is, therefore, imperative to carry out further research in order to clarify the variability in both the depositional, and possibly even stratigraphic, relationships between these units.

**Talk**

## High resolution heavy mineral analysis by automated Raman spectroscopy – Methodology and Application

**<u>Nils Keno Lünsdorf</u>, Jannick Kalies, Patrick Ahlers, István Dunkl, Hilmar von Eynatten**

*Georg-August-Universität Göttingen, Germany*

Identification and characterization of heavy minerals is one of the fundamental techniques in sedimentary provenance analysis and optical microscopy the tool of choice. However, optical identification is often biased by operator subjectivity. Typically, 200 transparent heavy minerals are counted implying that mineral species of low abundance might not be detected, counting statistics imply high uncertainty of mineral proportions, and opaque heavy minerals are ignored. Modern Raman spectrometers are highly automatable and can help to mitigate these issues.

This point-count approach starts by using a polarizing microscope to create high resolution mosaic images of a polished mount in transmitted and reflected light at high magnification. From this mosaic the measuring positions are selected and transferred to the Raman spectrometer. Depending on the heavy mineral assemblage, about 400 to 800 grains can be analysed per hour. A novel measuring routine ensures high quality spectra by changing the measuring parameters according to grain type (opaque vs. transparent). A modified version of the Rruff database is used in conjunction with the segmental hit quality index approach to automatically identify the mineral phases. Automated deconvolution can be applied to specific mineral groups to estimate chemical composition within solid solution series. As grains are referenced, specific interesting phases can be selected and easily transferred to other analytical instruments (e.g., electron microprobe (EMP) or LA-ICPMS) in order to perform single grain chemical or geochronological analysis.

The method was used to document the evolution of volcanic detritus during transport and to test if different volcanic sources can be discriminated in modern sediment. 700 to 1000 grains per sample and grain-size fraction (10 – 30 µm, 30 – 63 µm, 63 – 125 µm) of modern river sediments of the Fulda river in central Germany, which mainly drains sedimentary rocks of the Triassic Bunter Sandstone and Muschelkalk formations, but also Miocene volcanic rocks (basalts, trachytes, phonolites) of the Vogelsberg and Rhön area, were analyzed. Besides the heavy mineral assemblage, chemical compositions of pyroxenes, olivines and magnetites were estimated from the Raman spectra and cross-checked by EMP. In terms of chemical composition, the precision of the EMP is not reached, but the change in composition is similarly reflected by the Raman spectra. This allows, for instance, discriminating between diopsidic pyroxenes from basalts and trachytes. Results further reflect downstream dilution and modification of volcanic detritus, while aeolian input to the fluvial system is assessed by grain-size discrimination.

**Poster**

## Sandstone characterisation from the Neogene-age Tabernas Basin, SE Spain

**Heike Koch**[1], **Tom McCann**[2]

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The Tabernas Basin is a Neogene-age, E-W- trending, intramontane trough located in the Internal Zone of the Betic Cordillera in SE Spain. It is bounded to the N and NW by the Sierra de los Filabres, comprising predominantly high-grade metamorphic rocks of the Nevado-Filabride Complex, while the Sierra Gádor and the Sierra Alhamila, composed of lower-grade metamorphic rocks of the Alpujarride Complex, form the W and S margins, respectively. Towards the E, the Tabernas Basin is connected to the Sorbas Basin. In contrast to the latter, however, the sedimentary fill of the Tabernas Basin principally comprises deep marine sediment gravity flow deposits. Research on the basin has predominantly focused on the well exposed turbidite systems in the NW of the basin. These turbidite systems are capped by an inferred seismite, the Gordo Megabed, which blankets large areas of the Tabernas Basin.

Detailed sampling was carried out within the sedimentary succession of the Tabernas Basin (n=70) in order to provide a petrographic overview of the various bodies within the basin. Given that the basin was tectonically active over its lifespan, with movement largely controlled by the El Cautivo Fault Zone, the resultant basin topography was complex comprising a series of intrabasinal highs and lows which contained the sediment gravity flows, resulting in ponding and flow reflection. Our sampling strategy has attempted to include all of the main sedimentary bodies and basinal lows. The clastic sediments comprise mainly sandstones and conglomerates. Initial results suggest that the sandstones are quartz rich with subordinate amounts of feldspar, mica and rock fragments contained within a carbonate cement. Also present are a range of fossils and fossil fragments, as well as authigenic clay minerals. The sediments were mainly sourced from a topographically rugged, and tectonically active hinterland and transported over an equally steep cliff-lined coastline located to the N of the basin.

**Poster**

## Sediments of two Gondwana glaciations in Ethiopia: Integrated provenance analysis based on bulk geochemistry, heavy mineral assemblage and single-grain techniques

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The East African Orogen, which formed during the amalgamation of Gondwana, shed huge amounts of sediment towards the continental margins during the Palaeozoic. In Ethiopia, Palaeozoic sedimentary successions can be assigned to the two major Gondwana glaciations in the Late Ordovician and the Carboniferous–Permian. The distribution of ice sheets and continent-wide glacier dynamics during these glacial periods are still under discussion. The Arabian-Nubian Shield – the northernmost part of the East African Orogen – is a probable local source region for the sediments. However, far transport from central Gondwana (e.g., East Africa) is also possible. Ethiopia is a key region between potential distant sediment sources and the northern margin of Gondwana.

To assess differences in provenance, transport and weathering conditions, we compare sediments of both glaciations regarding their chemical composition, heavy mineral assemblage, rutile and garnet chemistry, and detrital zircon U–Pb ages.

For the Late Ordovician sandstones, the geochemical composition and the enrichment of ultra-stable heavy minerals indicate intense weathering and reworking prior to deposition, yet a facies dependency suggests a certain degree of post-depositional dissolution. Rutile is omnipresent and can be assigned to mainly amphibolite facies felsic source rocks. Only little garnet is present. The Carboniferous–Permian sandstones are less mature and show a more variable heavy mineral assemblage. The prevalence of garnet and apatite points to only slight influence of acidic weathering. Garnet chemistry reveals both igneous and metamorphic sources. Detrital zircons of both formations are mainly Pan-African in age. However, the Late Ordovician sandstones further contain prominent amounts of Tonian–Stenian (c. 1 Ga) and Palaeoproterozoic zircons. We assume an association with the Gondwana super-fan system. Besides Pan-African ages, the Carboniferous–Permian sandstones are characterised by c. 800 Ma old zircons, which may be derived from a local source.

**Poster**

## Towards a sediment budget of the Buntsandstein in Europe and its implication for palaeoenvironmental conditions at and shortly after the Permian-Triassic Boundary

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The palaeoenvironmental turnover at the Permian-Triassic Boundary (PTB) led to a strong increase of clastic sediment fluxes from the continents to the oceans, which is usually interpreted as the response to the deterioration of ecosystems, soil stripping, and a strong weathering regime. In western and central Europe this time interval is represented by the lithostratigraphic group of the Buntsandstein. To gain better insight into the dimension of sediment fluxes during Buntsandstein deposition, we calculated the sediment volume of the Lower, Middle and Upper Buntsandstein subgroups based on the compiled isopach maps of the Southern Permian Basin Atlas (SPBA). In the first step, the sediment distribution area in Lower, Middle and Upper Buntsandstein times was estimated by using the digitized isopach maps of the SPBA in GIS. Afterward, the average thickness of each area was calculated from isopach maps. The volume of sediments contained in an area can be estimated by multiplying the distribution area and the average thickness ($V=A\times T$). Accordingly, the volume of each interpolated sedimentary area was calculated for each time period. The extracted areas and volumes of each period illustrate a steady decrease from Lower, Middle and Upper Buntsandstein by 15 and 21% for the depositional area, and 23 and 45% for the sediment volume. The Lower, Middle and Upper Buntsandstein are estimated to span ~2, ~4.5 and ~1.5 million years, respectively. Using these time estimates the corresponding sediment fluxes are ~10.4, ~3.6 and ~5.9 $\times 10^{13}$ $m^3$/Ma. The strong decrease from the Lower to the Middle Buntsandstein supports the hypothesis of a strong clastic signal close to the PTB (little below or above the lithostratigraphic boundary depending on different authors). This signal decays over ca. 6.5 million years before a slight increase occurs in the Upper Buntsandstein. This increase may be explained by the wetter climate in the Upper Buntsandstein, higher transport capacities, but still sparse vegetation cover. So far, (bio) chemical sediments are not subtracted from this budget but are assumed to be small compared to clastic fluxes. Our next steps will involve refining this sediment budget and combining it with provenance data in order to correct for grain size, porosity and sediment recycling.

**Talk**

## Composition and provenance of upper Neoproterozoic and Cambrian sediments from Finnmark, Arctic Norway: Insights from a multi-method approach on the Digermulen Peninsula

**Guido Meinhold[1,2], Marlene Perschl[2], Maren Schröpfer[2], Annika Steichert[2], Jan Ove R. Ebbestad[3], Anette E. S. Högström[4], Sören Jensen[5], Teodoro Palacios[5], Magne Høyberget[6], Heda Agić[7], Wendy L. Taylor[8]**

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The remote Digermulen Peninsula by the Tanafjorden of north-eastern Finnmark, Arctic Norway, contains an almost complete sedimentary record across the Ediacaran–Cambrian transition as well as microfossils, macrofossils and trace fossils for studying the Ediacaran biota and the Cambrian radiation. It is one of the few localities worldwide and the only locality in Scandinavia where Ediacara-type fossils have been found. The site was located at the edge of Baltica during the Ediacaran–Cambrian transition, where potentially the dramatic climatic turnover from icehouse to greenhouse conditions can be deduced and tied to large-scale plate tectonics. The Digermulen Peninsula was first studied in the 1930s by Sven Føyn, who also published a geological map in 1937, emended by Harold G. Reading in 1959. In the following years, more detailed mapping was carried out by students from Oxford University. The exposed rocks on the Digermulen Peninsula belong to the Vestertana and Digermulen groups of the Lower Allochthon overlying the Baltic Shield. The succession consists mainly of quartz-rich sandstones and mudrocks. Deposition took place in various environments including fluvial, shallow marine and deeper marine settings. As shown by previous studies using palaeocurrent data, sediment supply was from the Baltic Shield toward the passive margin of Baltica in pre-Ediacaran time. At one point within the Ediacaran succession, it shifted by 180 degrees due to the newly formed Timanian orogen. This orogen formed in north-eastern Baltica during the late Neoproterozoic. It caused a change in source area due to the formation of the Timanian foreland basin to the east of Digermulen Peninsula. Extensive field and laboratory work by the Digermulen Early Life Research Group, with funding from the Research Council of Norway, allows for the first time a detailed analysis of sediment supply and to test current palaeotectonic models based on a multi-method provenance approach on Neoproterozoic and Cambrian mudrocks and sandstones of the Digermulen Peninsula. The methods include, amongst others, thin-section petrography, bulk-rock geochemistry (XRF, ICP-MS), bulk-rock mineralogy (XRD), conventional heavy mineral analysis, single-grain geochemistry (EMP) and zircon U-Pb geochronology. We present and discuss the first results to decipher the sediment sources and to track changes of sediment supply through this critical time interval of Earth's history.

**Talk**

## The role of the lower plate in providing provenance during Alpine convergence inception: Insights from detrital signatures of the Western Ligurian Flysch accretionary complex

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In the context of enormous crustal shortening and vast lateral displacement of oceanic units as observed in the Penninic domain of the Alpine orogeny, detrital signatures provide critical insights for appraising paleogeographic reconstructions and comprehending hinterland geology and tectonic events. Despite intensive research efforts and significant advances in the understanding of subduction and obduction processes that affected the Western Alps, the paleogeographic evolution of the Alpine Tethys represents a yet debated topic in Alpine geology, and within it, the role of the opposing continental margins (passive European margin and active Adriatic margin) as source regions for Cretaceous siliciclastic turbidites bordering the convergent system is particularly disputed. A multi-proxy provenance analysis (modal framework analysis, detrital zircon chronology, paleocurrent determination) applied to the two terrigenous superimposed units of the San Remo-Monte Saccarello Unit of the Western Ligurian Flysch complex – the Hauterivian-Santonian San Bartolomeo Fm. and the Campanian-Maastrichtian Bordighera Sandstones - is here used to solve this problem along the Ligurian Alps transect. Petrographic analyses characterize the basal complex sediments of the San Bartolomeo Fm. as quartz-rich sandstones defined by modal averages of Q69F29L2 and a mean P/K feldspar ratio of 0.48. By contrast, the conformably overlying Bordighera Sandstones represent texturally and compositionally immature first-cycle arkosic arenites (average modal composition: Q49F48L3; mean P/K-ratio: 0.57). A provenance evolution from a stable craton scenario and/or transitional continental provenance setting towards rapidly uplifted bedrock (granitoid plutons and low-grade metamorphic geobodies) can be inferred. New geochronological data (U-Pb detrital zircon ages) demonstrate that virtually the same source terranes provided the provenance for both formations. The detrital age spectra moreover display dominant peaks that are practically compatible with comprehensively documented magmatic and metamorphic pulses that affected the Southern Variscides. The strong affinity of the clastic detritus towards the Paleo-European margin underlines the importance of the lower plate (i.e. the passive margin) in providing the provenance for coarse-grained turbidite systems in pre-collisional convergent settings. Based on this observation, the arrival of a migrating flexural bulge at the continental margin of the lower plate is regarded to explain the inversion of the European margin, promoting the erosion of the stable continental shelf followed by the uplift of the continental block and rapid sedimentation without significant reworking processes as its hinge line traversed towards the hinterland.

**Talk**

## Deciphering the late Paleozoic to Mesozoic tectonosedimentary evolution of the northern Bohemian Massif from detrital zircon geochronology and heavy mineral provenance

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During the Late Paleozoic to Mesozoic times, the northern Bohemian Massif underwent a complex, multiphase intraplate deformation that can be inferred from the depositional record of Carboniferous–Permian non-marine basins and from the Bohemian Cretaceous Basin (BCB). For instance, the northerly Lusatian Massif has been deemed as an elevated crustal block during the entire Mesozoic and was presumably covered by Triassic to ?Lower Cretaceous sedimentary rocks that were re-deposited into Upper Cretaceous sandstones of Saxony (e.g., Voigt, 2009; Hofmann et al., 2018). Unlike the Saxonian Cretaceous, the NW part of the BCB comprises a more complete Upper Cretaceous (Cenomanian–Santonian) sections and, together with preserved relics of Jurassic and Permian, it is thus an ideal setting to discuss the above model.

In this study, we examine the protracted Late Paleozoic–Mesozoic tectonostratigraphic evolution of the northern Bohemian Massif using the detrital zircon geochronology and heavy mineral analysis. The newly obtained zircon age spectra reveal a similar trend to that recorded in the Saxonian Cretaceous. Cenomanian to uppermost Turonian sandstones are characterized by a dominant population of Variscan (Carboniferous) zircon ages with a minor contribution of Cadomian (late Neproterozoic) and Cambrian–Ordovician ages; older zircon ages are almost absent. Uppermost Turonian–Coniacian samples reveal more frequent pre-Cadomian zircon ages, which are interpreted to be of Baltica affinity, although not as apparent as in Hofmann et al. (2018). Compared to the data of Hofmann et al. (2018), our allegedly Jurassic sandstones show a monotonous zircon age spectrum with dominant Variscan age population. Permian sandstones show a conspicuous peak at ca. 2 Ga, which excludes these rocks as a source for siliciclastic supply to the the BCB during Santonian to ?Campanian times (cf. Hofmann et al. 2018). Santonian sandstones show a zircon age spectrum similar to Cenomanian–upper Turonian, indicating re-deposition of these rocks.

The heavy mineral analysis revealed that all the analyzed Cretaceous samples are characterized by predominance of ultrastable zircon–tourmaline–rutile (ZTR) assemblage, with a minor fraction of garnet, staurolite, monazite, and anatase, clinozoisite, topaz, and spinel as accessories. The ZTR assemblage dominates the Jurassic sandstone, although it is slightly depleted in rutile in comparison to Cretaceous sandstones. Higher content of monazite was detected in the upper Turonian–lower Coniacian samples as compared to older sandstones. This may indicate the presence of S-type granites in the source area.

Talk

## Application of SEM-based quantitative mineralogical analysis in the development of proxies for provenance and transport mechanisms of modern stream sediments

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Provenance analyses of stream sediments mostly rely on analytical methods such as bulk sediment geochemistry, mineralogy (provided by XRD) and single grain analysis. In this study, we focus on automated mineralogy by Mineral Liberation Analyser (MLA), as a potentially powerful tool for sediment provenance studies. The MLA combines backscattered electron (BSE) imaging with energy dispersive X-ray spectrometry (EDS) generating compositional data for all measured sediment particles (in this study, i.e. 20000 to 60000 grains and the including sub-grains). Resultant data include particle and mineral grain parameters (i.e. size and shape) as well as the mineralogical composition and properties (e.g. elemental composition, density) of each particle and its individual constituting mineral grains. Necessary, robust statistical analyses are part of the study, to maximize the use of the voluminous set of data provided by MLA. These statistical analyses unveil trends and dependencies in suites of related samples. This is illustrated here in a case study. We combine bulk geochemistry, XRD and MLA analyses. On the one hand, in order to make a comparison of the selected methods, and on the other hand, to ensure the quality and to critically assess the benefit of MLA data.

The study area is located in the Vogtland region of the Free State of Saxony (Germany). The bedrock mainly consists of Variscan-aged basement rocks. These rocks comprise plutonic (i.e. different types of granite) and metamorphic units (mica schists, phyllites and quartzites), which are very well studied.

With first results of the study, it becomes apparent that changes in provenance and transport features of the unconsolidated sediments are easily identified, based on the modal mineralogy, geochemical changes and grain-parameter patterns. Using the MLA we can detect and calculate the relative composition and amount of anthropogenic contamination within the sediment. Furthermore, mixing of the material is calculated with respect to the relationship between lithological changes and the river path. The examination of shape features on single grains, such as potential marks of corrosion, leaching, abrasion and fractionation, provide the possibility to implement efficient proxies, which can be related to weathering and transport mechanisms.

Talk

## Advances in garnet-single grain analysis: Mineral inclusions record HP/UHP provenance

**Jan Schönig**[1], **Guido Meinhold**[1,2], **Hilmar von Eynatten**[1], **Nils Keno Lünsdorf**[1]

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Metamorphic rocks are classified by their composition and metamorphic grade. The differentiation is mainly based on diagnostic associations of minerals in mutual grain contact, i.e., metamorphic mineral assemblages. In sedimentary provenance analysis, this information is primarily not available due to the grain-size range of the sampled sediments, mainly sand-sized or smaller, which makes an analysis of pebbles or larger-sized material impossible. Thus, we are restricted to mineral grains which lost their paragenetic context and forced to receive information about metamorphic source rocks from specific index minerals or geochemical characterization of single mineral phases (von Eynatten & Dunkl, 2012, Earth-Science Reviews).

Index minerals like glaucophane, lawsonite, omphacite, kyanite or coesite reflecting high- and ultrahigh-pressure (HP/UHP) source rocks, respectively, are rarely well preserved due to the common replacement by lower-grade phases during retrograde metamorphism, and their low mechanical and/or chemical stability. Besides some fingerprinting or thermometry methods on single mineral phases, especially the discrimination of metamorphic sources by major element composition of detrital garnet is an often used and well-established tool in sedimentary provenance studies. Although quite advanced, all garnet discrimination schemes are affected by at least one of the following drawbacks: (i) garnets from different source rock types show geochemical overlap and cannot be classified unambiguously, (ii) different protolith compositions cannot be differentiated, and/or (iii) advanced discrimination within the HP/UHP region does not exist.

In this study, we introduce an advanced development of garnet single-grain analysis by considering mineral inclusions, which enables the analysis of metamorphic mineral assemblages in the detritus. By a case study of modern sand samples from the Western Gneiss Region of SW Norway, we demonstrate that (i) important metamorphic index minerals occur as inclusions in detrital garnet, suggesting that these will be preserved in the sedimentary record as long as garnet is stable, (ii) the inclusions are useful indicators for HP/UHP sources, and (iii) the presence and distribution of specific inclusion types can be used to support and enhance the provenance information given by geochemical garnet compositions. Furthermore, the presence of intact and monomineralic coesite inclusions in one of the sand samples is of particular importance, indicating the presence of UHP rocks in the catchment. This opens new opportunities for the prospective exploration of UHP rocks in the geological record by analyzing sediments and sedimentary rocks instead of being limited to outcrops of crystalline rocks (Schönig et al., 2018, Scientific Reports).

# 5c) Tectonics & sedimentation – From fractures to basins

Talk

## Iceberg scour marks in the northwestern offshore Germany

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The uppermost seismic units in the North Sea, NW offshore Germany, have been studied systematically based on industrial multichannel 3D seismic data. The Quaternary sedimentary succession reaches a maximum thickness of more than 1000 m in the central North Sea. The Quaternary is characterized by at least three extensive glaciations which covered large parts of the North Sea and adjacent land areas. As a result of these glaciations, we find today several glacial forms like tunnel valley systems and iceberg scour marks onshore and in the offshore North Sea. The latter, are well-documented from a variety of present-day and formerly glaciated marine environments and are the result of scraped iceberg-keels into soft sediments of the seabed.

Iceberg scour marks on the former sea floor developed as elongate lineations on seismic horizon and amplitude maps. Our seismic investigations exhibit lengths between 0.1 km and 23 km, widths between 15–50 m, and 6–12 m deep incisions. They are found between 300–850 m at a present-day depth with main occurrences between 500 and 700 m depth. Locally, they cross-cut each other at a wide range of orientations, but regionally there is a distinct NNW-SSE to N-S orientation. In places a correlation with bright spot accumulations is visible. For the Dutch offshore sector Kuhlmann and Wong (2008) suggested that the iceberg scour marks in the study area can be attributed to younger Gelasian age (~2.1 Ma). However, our data show that these ice scours even occur already at the beginning of Northern Hemisphere Glaciation (NHG) around 2.6 Ma.

Distinct iceberg scour marks detected on 3D seismic data are considered as a robust indication that the formerly affected surfaces of the southern North Sea were deposited under shallow marine conditions with water depths not exceeding 100 m during the Quaternary. In this study these glacial features on the former sea floor are used as chronological markers and thus as measures for the Quaternary subsidence analysis within the German North Sea. Since most Quaternary sediments were deposited in a shallow-water environment the southern part of the North Sea basin must have experienced an extremely high rate of subsidence exceeding average Cenozoic rates by a factor of 10 as revealed by Cenozoic thickness maps. Here, we show that compaction and load-induced subsidence alone explain about 75% of the observed Quaternary subsidence. Thus, a certain portion of the subsidence needs additional processes to be invoked.

Talk

## The discontinuous Lower Cretaceous of NE Germany: The missing link of Late Cimmerian Unconformity and Late Cretaceous inversion?

**Sandra Franke**, **Matthias Franz**

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The Late Cimmerian Unconformity and Late Cretaceous inversion are key elements in the late Mesozoic evolution of the North German Basin (NGB, Ziegler (1990)). In the eastern NGB, erosional unconformities within the Lower Cretaceous succession witness noticeable syn-sedimentary tectonics between the two major phases of intraplate tectonics. Related to the Early Cretaceous tectonics, small and isolated ENE-WSW to NE-SW oriented grabens evolved in Northeast-Germany at the Darß peninsula and islands of Rügen and Usedom. In these areas, Lower Cretaceous sediments unconformably follow Liassic sediments representing the Late Cimmerian Unconformity. In the grabens, the discontinuous Lower Cretaceous successions are up to 450 m thick contrasting with a few metres to decametres thick successions outside the grabens. On detail, Berriasian-Lower Valanginian, Barremian and Upper Aptian sediments are only present in the grabens whereas remnants of upper Hauterivian and Upper Albian sediments are present outside and in the grabens. A detailed study integrating sedimentological, biostratigraphical and seismic methods gives insights into Early Cretaceous tectonics characterised by subsidence and sedimentation alternating with uplift and substantial erosion (inversion).

(1) Biostratigraphic and sedimentological data of up to 450 m thick Lower Cretaceous sediments reveal Berriasian-Early Valanginian, Late Hauterivian, Late Aptian and Late Albian phases of subsidence and wide-spread coastal to marine sedimentation. (2) The discontinuous Lower Cretaceous successions suggest Late Valanginian-Early Hauterivian, Early Aptian and Early Albian phases of uplift and erosion. (3) The alternation of subsidence and uplift (inversion) coincide with graben formation, fault tectonics and salt diapirism in NE Germany (Beutler et al., 2012). (4) The widespread occurrence and balanced thickness of the Cenomanian in NE Germany mark the cessation of Early Cretaceous tectonics. (5) The Early Cretaceous tectonics may represent both, descendant phases of the Late Cimmerian Unconformity and ascendant phases of the Late Cretaceous inversion.

References

Beutler, G., Junker, R., Niediek, S., Rößler, D., 2012. Tektonische Diskordanzen und tektonische Zyklen im Mesozoikum Norddeutschlands. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften (163/4), 447–468.

Ziegler, P., 1990. Geological Atlas of Western and Central Europe, 2nd ed. Shell Internationale Petroleum Maatschappij B.V., Den Haag, 239 pp.

**Talk & Poster**

## Tectonic controls on the Burdigalian transgression of the Upper Marine Molasse inferred from the stratigraphic architecture

**Philippos Garefalakis**, **Fritz Schlunegger**

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Interpretations of marine transgressions have been contested because of multiple possible controls. This has particularly been the case for the Upper Marine Molasse (OMM) deposited north of the evolving Alps, where the 20 Ma-old Burdigalian transgression has either been related to a tectonic, eustatic or surface control. Here, we reassess this problem through a detailed sedimentological analysis of 7 OMM sections in Switzerland.

At the eastern proximal basin margin, the OMM starts with a 350 m-thick sequence of parallel-laminated sandstones. Cross-bedded sandstone interbeds with basal scours and pebbly lags also occur. These observations suggest deposition by waves in a foreshore to shoreface environment. Transcurrent laminations imply a W-E trending coastline sub-parallel to the Alpine front. A marked change is recorded at ~19.5 Ma by the first-appearance of m-scale sandstone cross-beds. Individual foresets are superimposed by flow ripples and muddrapes, suggesting deposition by tidal currents in a lower shoreface to offshore environment. The total 900 m-thick section ends with a m-thick palaeosoil, formed at 19 Ma.

Approximately 75 km farther west, the ~20-19 Ma-old OMM sequence is 350 m thick and starts with a ~10 m-thick stack of 2-3 m-high sigmoidal delta-clinoforms with a pebbly lag. This is overlain by a suite of cross-bedded sandstones with muddrapes. This ensemble suggests deposition within an estuary environment. Similar to the east, deposition of sandstone cross-beds with diameters >10 m and muddrapes started at ~19.5 Ma and marked a shift towards a tidal-dominated, offshore environment. The section ends with a tidal flat at ~19 Ma.

Seismostratigraphic correlations show that in the distal basin ~25-30 km farther north, sedimentation started at ~19.5 Ma. There, the occurrence of up to 5-10 m-high fossiliferous sandwaves suggests deposition in an offshore environment. Palaeoflow data imply that prior to 19.5 Ma, sediment transport occurred towards the NE. This pattern changed to an axial transport after 19.5 Ma, and finally to a NNW-directed discharge at ~19 Ma.

Our observations suggest that the Burdigalian transgression was associated with a deepening and widening of the basin between 20-19.5 Ma, followed by a tilt of the basin axis from the NE to the NNW when the basin became filled. While surface and eustatic controls could have contributed to depocenter shifts, the large-scale stratigraphic evolution, the changes in the basin geometry and the shifts in palaeoflow directions most likely occurred in response to the 20 Ma-old delamination of the Aar massif in the Alps.

**Poster**

## GIS-based DEM5-LiDAR lineament analysis and fault-slip data from the Kaiserstuhl volcanic edifice and first structural data from the Vogelsberg volcanic field: Implications for Neogene deformation in the Upper Rhine Graben area

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Cenozoic deformation in the Upper Rhine Graben is essentially derived from syndepositional faults in 2D-seismic geological sections constructed from drillhole and seismic data and fault offsets (see Grimmer et al. (2017) for a review and further references): Paleogene WNW-extension was overprinted by Neogene to recent NE-transtension. In order to test this concept, the Miocene (19-14 Ma) Kaiserstuhl volcanic edifice in the southern part of the Upper Rhine Graben was studied for its deformation by a highly resolved LiDAR-based Digital Elevation Model (DEM) and structural field data.

DEM reveals three preferred orientations of linear features: NE-SW, NW-SE, and NNE-SSW. These trends are similar to orientations of minor faults documented in outcrops of the Neogene Kaiserstuhl volcanic edifice: Older NW-striking sinistral extensional faults and NE-striking, dextrally sheared dykes were offset by NW-striking normal faults thus representing a younger fault population. This younger fault population is characterized by N-S-striking sinistral oblique strike-slip faults and NW-striking normal faults, which are the major structural trends that are also identified in geothermal reservoirs and by fault-plane solutions of natural earthquakes in the Upper Rhine Graben. These structures are thus compatible with the regional stress field. Stress inversion of fault-slip data refers to an older N-S-transtension along NW-striking sinistral oblique strike-slip faults and minor NE-striking dextral oblique strike-slip faults, followed by the recent stress field. Both deformation phases are compatible with W- and NW-striking joints indicating N-S-extension and NE-SW-extension, respectively. Dykes in the Kaiserstuhl volcanic edifice strike predominantly (N)NW, NNE and NE and thus subparallel with lineaments and fault trends. Few joint and fault-slip data indicate a third, possibly the oldest, phase characterized by (W)NW-(E)SE-transtension. Reconnaissance structural analysis in the Neogene Vogelsberg volcanic field emplaced on the NE-trending transfer zone between the Upper Rhine Graben and the Hessian Graben system revealed similar fault-slip data. These heterogeneous fault-slip data from the Neogene volcanic rocks thus indicate a more complex deformation history than commonly considered for the Upper Rhine Graben.

Reference

Grimmer JC, Ritter J, Eisbacher GH, Fielitz W (2017). *IJES* 106, 827-853.

**Poster**

## The interaction between tectonics and carbonate-system development in western offshore Libya

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This study presents 3D-seismic geomorphological and sedimentological interpretations of carbonate systems in the Tripoli-Sobrata Basin, Mediterranean Sea, western offshore Libya, based on 3D-seismic-reflection data and 13 industrial wells. The study area encompasses several large hydrocarbon fields, which are of major economic importance for Libya. Yet, despite the clear relevance and value, there are today open questions concerning the tectonic and stratigraphic processes that controlled carbonate platform and reservoir development through time.

In this research a new workflow is used that is specifically designed to enhance the seismic interpretability of subsurface carbonate systems and reservoirs. The workflow integrates targeted 3D-seismic data pre-conditioning and comprehensive 3D-seismic spectral decomposition analysis. The subsurface interpretations show that (1) the structural orientation of several major hydrocarbon-bearing carbonate systems is oblique to the main NW-SE fault trend. Folding and the preferential growth of carbonate platforms at the top of folds pre-dates NW-SE-oriented faulting, and was only secondarily affected by brittle tectonics. The structural interpretations presented can be used for fracture prediction in carbonate systems. (2) The seismic interpretations indicate that diagenetic changes within the main reservoir limestones (e.g. dolomitisation; burial corrosion in relation to underlying salt) can be imaged on 3D seismic-reflection data by detailed 3D spectral decomposition analysis. The combined tectonic and stratigraphic interpretation approach presented can serve as a universally applicable template for refined 3D seismic-based reservoir prediction in subsurface carbonate systems.

**Talk**

## The Olga Basin in the northern Norwegian Barents Sea (Arctic) – a Caledonian or Timanian affinity?

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The epicontinental Barents Sea experienced multiple stress regime changes including Paleozoic continental collision, multi-stage late Paleozoic to Mesozoic rifting and late Cenozoic uplift and erosion. While the SW Norwegian Barents Sea is well covered by academic as well as industry-driven studies the tectonic evolution of the NE Norwegian Barents Sea is only known from sparse seismic data and geological data from the Svalbard and Franz Josef Land archipelagos. Magnetic data reveal a NNW-SSE trend in the NW Barents Sea which appears to line up with N-S striking structures on Svalbard. A second NE-SW striking Caledonian arm is assumed to run through this region crosscutting almost perpendicular important structural elements such as the Olga Basin.

We acquired geophysical and geological data in the wider area of the Olga Basin southeast of Svalbard in 2015 in order to reconstruct the basin evolution with regard to inherited structures. The obtained data include ~1750 km of 2D multi-channel seismic lines, ~350 km of wide angle seismic lines by means of sonobuoys, sediment echosounder data, multi-beam data and potential field data.

Interpretation of the seismic profiles reveal a post-Caledonian Olga Basin which developed as W-E striking halfgraben bounded by a W-E trending normal fault in the north. By additional analysis and interpretation of potential field data and vintage seismic lines (BGR74, BGR76) we suggest a Paleozoic basin system. Interestingly, the basin system is characterized by unusual positive magnetic and gravitational anomalies. The correlation of the earliest subsidence phase and magnetic and gravity anomalies with the preservation of Cretaceous sediments indicates that deeper inherited structures again influenced the Cenozoic basin inversion. The basin axis neither fits the assumed Caledonian trends nor to the striking of Carboniferous rifting for that region. We speculate whether this Paleozoic basin system developed entirely independent from proposed Caledonian structures or whether this region has even a Timanian affinity.

**Poster**

## Giant pockmark formation from Cretaceous hydrocarbon expulsion in the western Lower Saxony Basin, The Netherlands

**Frank Strozyk**, **Lars Reuning, Stefan Back, Peter Kukla**

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A field of giant pockmarks was discovered at the base of the Upper Cretaceous Chalk unit in the westernmost Lower Saxony Basin in The Netherlands. 3D seismic and well data show that mostly circular, 300–850 m-wide and 10–50 m-deep, pockmarks formed at the top of the

Lower Cretaceous Upper Holland Marl Formation, which overlies oil- and gas-filled Lower Cretaceous sandstone reservoirs in the vicinity of the study area. Based on our interpretations, we present a scenario of early gas generation in Carboniferous coals and a localized migration of the gas from its original subsalt reservoirs through a salt weld in the Zechstein evaporites into the shallow Cretaceous sandstone reservoirs and the fine-grained marl above. Diapiring salt walls thereby limited the gas migration and trapping to a 150 km2-sized basin. A sea-level drawdown during Base Chalk formation possibly led to excess pore pressure in the reservoir and the breaching of the seal close to the seafloor, which caused a short-lived expulsion of the gas and pockmark formation. While hydrocarbon generation, migration and trapping are common processes in this region, gas escaping at the seafloor with pockmark generation appears to be a rather rare and complex phenomenon. In general, the presence of pockmarks associated with salt welds may be used to constrain the timing and migration pathway of hydrocarbons from subsalt into shallower reservoir levels. Both features may imply a general reservoir potential for regions where suitable source rocks are missing in the post-salt succession.

**Poster**

## Salt structures in the German North Sea: New results by re-evaluation and systematic classification

**Heidrun Louise Stück, Fabian Jähne-Klingberg, Frithjof Bense, Marco Wolf**

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The actual knowledge about salt structures in the German North Sea grew continuously since the 80's. However until now, a high-detailed and coherent synthesis of salt structure genesis on the base of detailed 3D structural models is missing. The present study, embedded in the project "Subsurface potentials for storage and economic use in the North German Basin" (German acronym "TUNB"), aims to fill this gap by a comprehensive 3D approach, considering all salt structures and the interpretation of local to regional structural and sedimentary history.

Based on all available seismic data (from the 1960´s until today) we perform a systematic classification of salt structures, where type, geometry and the timing of evolutionary stages, relationship to sub-salt faults, subsidence history of rim synclines, timing of salt structure burial, bulging of roof sediments, the evolution of crestal faults, salt glacier or lateral intrusions as well as halotectonic mobilisation of Upper Rotliegend salt-bearing members are considered. Besides a high detailed seismic interpretation and 3D modelling of salt structures, our analysis comprises also the analysis of kinematics and interpretation of Mesozoic to Tertiary sedimentary successions surrounding the salt structures. Additionally we consider interpretative uncertainties that come along with the seismic imaging of salt formations caused by generalisation, heterogeneous data distribution, seismic interpretation itself, and accompanied by a bias of the interpreter. Therefore, we map the extent of uncertain areas:

i) the loss of seismic resolution,

ii) the most probably, interpreted outline based on the geological constraints and an iterative 3D interpolation, and

iii) an envelope highlighting chaotic seismic pattern that could indicate salt bodies.

First results indicate that some salt structures need to be revised with respect to their presence, shape, geometry, position, kinematics or evolutionary stages as well as show often close relationship with fault zones. Also salt rollers are often observed, which, rarely described before. Seismic-stratigraphic studies of Triassic successions reveal that salt structure genesis in the central German North Sea is characterised by e.g.:

i) first mild salt mobilisation in the Horn Graben in the Upper Middle Buntsandstein,

ii) start of major salt movements in the Upper Buntsandstein - Muschelkalk along rift structures (reactive diapirism) like the Horn Graben, with some temporal delay along the Ems-Lineament and other parts of the southern German North Sea,

iii) a more differentiated spatial evolution of salt-structures from Muschelkalk to Keuper than previously expected.

**Talk**

## Late Eocene start of Cenozoic Deformation in the Central Tien Shan – evidence form the western Ili Basin (Kazakhstan)

**Thomas Voigt[1], Benjamin Leipold[1], Robert Scheuer[1], Istvan Dunkl[2]**

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The Ili Basin in southeast Kazakhstan is one of the large foreland basins of the Tian Shan and comprises a Cenozoic succession of strongly varying thickness. It developed in the course of the India-Asia convergence and is surrounded by high mountain ranges of the Tien Shan. The basement of the Ili-Basin consists mainly of Permocarboniferous magmatic rocks (Ili-Balkahsh Magmatic Belt). Clastic continental deposits of Paleogene to Neogene age cover a strongly weathered peneplain and show clear grain-size trends from margins to the central basin. Depocentres are located in foreland basins (up to 4000 m) and in NW-SE striking pull-apart basins. The Ili-basin is progressively deformed recently, resulting in the formation of intrabasinal anticlines and fault-bordered basement uplifts. The basement of the Ili Basin and major parts of the bordering mountain ranges show uniform Cretaceous AFT cooling ages, which were attributed to a precursor deformation event during the Cretaceous. Only the frontal range of the Trans-Ili Alatau and higher parts of the Dzhungar Alatau

AFT-cooling ages of 17-10 Ma (Macauley et al. 2013, 2014, De Pelsmaeker et al. 2015). Nevertheless, these data are not in agreement with the Ili-Basin evolution. We conclude a much earlier start for deformation based on the following observations:

1. Subsidence and deposition in the depocentres reflect a continuous sequence from late Eocene to recent.
2. Progressive unconformities and growth strata at the uplift margins involve the whole succession from Late Eocene to recent with continuous deformation rates.
3. Alluvial fan deposits occur within all formations close to the mountain ranges.
4. Provenance of late Eocene and Oligocene/Miocene fluvial deposits point to a source of metamorphic rocks, recently exposed in the high mountain ranges of the Jungar Alatau and the Bohoro Shan.

Old U/TH-He ages obtained from intrabasinal uplifts indicate very low erosion rates. This is in agreement with the preservation of exhumed basement surfaces, even in anticlines which started to growth in the Miocene. The contradiction of AFT-ages and sedimentological data is explained by slow exhumation in the early stages of mountain uplift and low denudation rates. The onset of fission track preservation needs about 2-4 km erosion. This leads to a significant delay of observed cooling ages to the real start of tectonic activity. The widespread late Mesozoic cooling ages of the basement are explained by regional uplift and not by activity of thrusts, because no evidence for Mesozoic foreland basins can be observed.

# 5d,g,i) Marine systems

Talk

## 3D seismic sedimentology and stratigraphic architecture of prograding clinoforms, central Taranaki Basin, New Zealand

**Stefan Back[1], Maximilian Franzel[2]**

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Three-dimensional (3D) seismic-reflection analysis of a major Miocene to Pleistocene (ca. 18 to 2 Ma) clinoform succession of the central Taranaki Basin offshore New Zealand reveals two distinct intervals of downbuilding progradation (ca. 7.5 to 6 Ma; and ca. 4 to 2 Ma). Kilometre-scale downbuilding clinoforms with straight upper foreset gullies initiate at the clinoform breakpoint, in places connected to topset distributary channels. Foreset mass-transport complexes occur mainly in the basal parts of downbuilding clinoform successions. Upbuilding progradational clinoforms are generally smaller, with topsets in places characterised by beach ridges and tidal channels. The foresets and bottomsets of the upbuilding clinoforms contain large gullies and sinuous deepwater channels, locally connected to topset channels. Retrograding units of the studied succession lack a distinct clinoform geometry, show few slope channels and gullies, and are characterised by extensive landward-stepping networks of shallow-marine and fluvial channels.

The 3D seismic-reflection analysis of the ca. 2000 $km^2$ study area allows an exemplary 3D documentation of migrating depositional systems along a highly progradational clastic margin, constrained by a stratigraphic framework tightly defined by the two intervals of major depositional downbuilding. The Late Miocene downbuilding is interpreted as solely forced by tectonic uplift. In contrast, the Pliocene-Pleistocene downbuilding is interpreted as dominantly controlled by eustasy in an overall subsiding back-arc environment. Excellent preservation particularly of the 4 and 2 Ma clinoform topsets provides unique insights into depositional systems at and above the shelf break, imaging palaeo-shoreline and palaeo-backshore environments. The detailed 3D clinoform analyses presented contribute to the understanding of clastic sedimentation processes from shelf to slope, which can be used to predict deepwater depositional facies.

Poster

## The proximal Late Cretaceous epicontinental shelf of northern Germany: a five-component depositional system

**Michaela Berensmeier[1], Bettina Dölling[2], Gianluca Frijia[3], Markus Wilmsen[1]**

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Marine environments are often described as three-component systems related to their predominant sediment composition comprising organic matter, carbonate, and siliciclastic sediment. The integrated litho-, micro- and biofacies analyses of new sections in the Ruhrgebiet (northwest Germany) led to the reconstruction of a more complex facies model deciphering the nearshore part of the Cenomanian–Coniacian shelf system of the Münsterland Cretaceous Basin (MCB). The integrated facies analyses of three stratigraphically well-dated sections led to the identification of three principal facies associations: (I) transgression conglomerates deposited on the proximal inner shelf under very high to moderate water energy, (II) greensand facies with a high, partly rock-forming content of green marine clays (glauconies) deposited under moderately high water energy (transgressive sand sheets of the protected inner shelf), and (III) spiculitic, silty-sandy marl facies deposited on the proximal middle shelf under low water-energy conditions. The shallow marine depositional setting was characterised by five main sediment sources: (1) the siliciclastic input coming from the Rhenish Massif in the south, (2) the skeletal grains of benthic, calcareous heterotrophs such as foraminifers, mollusks and echinoderms, (3) planktic carbonate (predominantly nannofossil micrite and c-dinocysts), (4) biogenic silica, mainly coming from siliceous sponges, and (5) green authigenic clays, (glauconies). Organic matter also played a role in the depositional system, mainly in triggering favourable redox conditions for glaucony formation close to the sediment-water interface. The detailed morphological and geochemical study of these (par-)autochthonous green clays allows to reconstruct their genesis in a specific marine palaeoenvironment. The herein presented study provides a refined model of depositional environments and sedimentary dynamics at the southern margin of the Late Cretaceous epicontinental sea in the MCB. However, the sedimentary setting cannot be explained by the doctrine of uniformity alone because the massive formation of greensands in nearshore environments has no analogue in recent systems.

Talk

## High resolution reconstruction of the Pleistocene-Holocene depositional systems in the German Wadden Sea (Southern North Sea) by means of parametric echosounder and core data – The WASA (WAdden Sea Archive) Project

**Ruggero Maria Capperucci**[1], **Schaumann Robin**[2], **Bungenstock Friederike**[3], **Bartholomä Alexander**[1]

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The Wadden Sea is well known as an archive for Quaternary climatic and sea level changes. Over the last years, evidences were found that following the last glacial phase (Weichselian) the sea-level drop and the absence of a proper glacial cover allowed human settlements northern than the present coastline. A better understanding of the processes and timing connected to the Quaternary high-frequency sea-level fluctuations is necessary to improve our knowledge about human strategies in response to climatic changes during the last few thousand years and to forecast the impact of the present sea-level rise on the coastal system development. The reconstruction of the Holocene palaeoenvironments is the focus of the WASA project (WAdden Sea Archive), which gathers experts from different disciplines (sedimentology, geophysics, palaeontology, palaeobiology, archaeology).

Over the last two years, surveys were carried out offshore and in the backside of the East Frisian island of Norderney, coupling multi-frequency subbottom-profiler (parametric echosounder) and sediment core data in order to:

- characterize the Middle- Upper-Pleistocene succession;
- map the Holocene base and compare it with the existing models;
- assess the Holocene evolution of the lower shoreface to offshore transition of the barrier island system;
- reconstruct the post-glacial palaeolandscapes and their evolution;
- find or exclude potential locations for human settlements.

First findings show the presence of multi-stacked, deep buried channels offshore Norderney. The origin of such drainage system could be either related to the Elbe palaeovalley and its tributaries (glacial phase), or to the migration of the barrier island system southward, following the rise of the sea-level during the Middle-Holocene.

In the back-barrier of Nornerdey, the combination of acoustic and core data allowed a detailed reconstruction of the Middle- to the Upper-Pleistocene deposits (previously based only on single cores). A complex erosional pattern was observed, with pre-Saalian and Saalian sediments preserved in the eastern sector of the tidal flat-island system, and Eemian marine deposits in its western part. Core facies analysis and, where present, a specific acoustic pattern corresponding to peat deposits were used for tracking the Holocene base and for updating the existing models.

Talk

## How new deep-sea observations change turbidity current models

**Matthieu Cartigny**

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The ocean floor comprises two thirds of our planet, and it hosts spectacular networks of channels and canyons formed by often powerful episodic sediment-laden flows, called turbidity currents. These submarine channels can extend for thousands of kilometres into the deep ocean, and are fed by submarine canyons that are as big as the Grand Canyon. The turbidity currents that created these channels remain poorly understood, as measurements of their velocities and sediment concentrations are only available in seven locations worldwide. This lack of observations reflects the relatively inaccessible and powerful nature of the flows, some of which powerful enough to drag 2,000 kg anchors for kilometres along the ocean floor. Fortunately, new technology now allow us to monitor turbidity currents in unprecedented detail.

These new field observations are important as turbidity currents are of societal and economic relevance. These flows are the main supplier sediment, organic carbon and nutrients to much of the deep-sea, as turbidity currents rival rivers in their global capacity to transport sediment across our planet. These fluxes make turbidity currents an important part of the carbon cycle that affects long term climate change, and they sustain rare ecological communities on the deep sea bed. Turbidity currents pose a hazard to submarine infrastructure, and have forced pipeline operators to invest millions of dollars in re-routing pipelines. Furthermore, these flows create the largest sedimentary bodies on our planet (e.g. the Bengal submarine fan holding tens of million $km^3$ of sediment), and these sedimentary body host a significant part of our oil and gas reservoirs.

Here I will present observations of three turbidity current monitoring sides: submarine channels in Canadian fjords, Monterey Canyon and the Congo Canyon. The observations show that turbidity currents can substantially deviate from the textbook models. The dynamics of the observered turbidity currents are controlled by a fast-moving and dense frontal cell that set-up the more dilute cloud that is seen in most models. Additionally, the observations show a bifurcation in the behaviour of the flows, where a flow either develops as fast and dense or as slow and dilute. Furthermore, the flow observations are link to their sedimentary deposits. This direct link between flow dynamics and deposits can provide valuable insights into the dynamics of turbidity currents throughout geological times.

Poster

## Hardened faecal pellets as a significant component in deep water, subtropical marine environments

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Hardened faecal pellets are classically interpreted to form in shallow, tropical environments. However, faecal pellets deposited in deep, subtropical marine conditions are poorly studied. IODP Site U1460 on the Carnarvon Ramp (SW Shelf of Australia, 214.4 m water depth) recovered a nearly continuous Pliocene to Recent record of outer shelf sediments deposited at the transition between cool and warm water environments. Below the depth of ~20 m (CSF-A) the relative abundance of sand-sized faecal pellets varies between 0 and 69 %. The origin and composition of the faecal pellets were investigated using scanning electron microscopy, binocular microscope and X-ray diffraction (XRD). The faecal pellets have a uniform size and shape and tend to occur mainly in relatively deeper water during interglacial times. They are mainly composed of skeletal fragments such as ascidians spicules, planktic foraminifera, sponge spicules and coccolith plates in a mud-sized matrix. The pellets therefore show an identical composition compared to the surrounding matrix, indicating that they have formed in situ. X-ray diffraction shows that the faecal pellets consist of aragonite, low-Mg calcite and dolomite. The aragonite at this study reaches up to 30% of the total bulk sediment and generally decreases with depth due to either dissolution or platform progradation. Aragonite dissolution within the faecal pellets is visible, e.g. at the tips of the ascidian spicules. The presence of framboidal pyrite within the pellets indicates bacterial-sulfate reduction (BSR). BSR likely explains the observed aragonite dissolution, which is accompanied by an alkalinity increase and in consequence by the precipitation of calcite and dolomite cements. The occurrence of pyrite in a depth starting at 5 m (CSF-A) indicates that aragonite dissolution and calcite cementation already started in the very shallow burial environment. We suggested that the faecal pellets are hardened due to this early cementation by calcite and therefore can be preserved in the fossil record.

Talk

## Discerning allocyclic and autocyclic controls on submarine fan development

**Ross Ferguson[1], Ian Kane[1], Joris Eggenhuisen[2], Florian Pohl[2], Mike Tilston[2], Yvonne Spychala[2], Rufus Brunt[1]**

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Submarine fan development is dependent on the interplay between allocyclic and autocyclic controls that dictate the timing and distribution of sediment supply on the slope and basin floor. Allocyclic controls are external to the sedimentary system and include sea-level, climate, and tectonics whilst autocyclic controls are internal to the system and include processes such as channel avulsion, levee growth and compensational lobe stacking. There is continued debate over the degree of control exerted by allo- and autocyclic mechanisms and the relative timescales at which they operate. Here, successive experimental sediment-laden turbidity currents with incrementally increasing then decreasing sediment supply rates have been used to emulate the effect of a waxing to waning sediment supply cycle on submarine fan evolution. When sediment supply rate was increased, an associated increase in channel incision and overbank deposition (levee growth) was observed on the slope, with concurrent lobe progradation on the basin floor. Conversely, when supply rate was lowered, the opposite was recorded: a reduction of channel incision and overbank deposition, and progressively back-stepping lobe deposits that onlapped the slope. These observations suggest a direct correlation exists between sediment supply and submarine fan architecture and that predictions about sediment distribution can be made on this basis. However, topography created by deposits from earlier turbidity currents caused subsequent flows to divert around them, favouring topographic lows and promoting lateral spreading and compensational lobe stacking. Continued lateral spreading resulted in a decrease in accommodation space on the basin floor, exacerbating the back-stepping trend of lobe deposits documented during the waning phase of the sediment supply cycle. The morphodynamic evolution recorded in this study indicates that allocyclic factors may drive initial conditions, but progressively, autocyclic topography assumes a relatively larger role in fan development, promoting back-stepping and possible avulsion of the system. These results have implications for our understanding of stacking patterns observed in outcrop where abrupt tops are commonly observed in deposits from basinal deep-marine systems, and for the distribution of sediments in larger-scale subsurface datasets.

Talk

## Authigenic carbonate formation in Lake Neusiedl - biotic and abiotic contributions

**Dario Fussmann[1], Avril von Hoyningen-Huene[2], Dominik Schneider[2], Andreas Reimer[1], Rolf Daniel[2], Gernot Arp[1], Patrick Meister[3]**

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A sampling campaign to Lake Neusiedl, conducted in August 2017, revealed new insights regarding the precipitation, pore water chemistry and the microbial impact on formation of fine grained carbonate sediments. Lake Neusiedl, located in eastern Austria, comprises a surface area of more than 300 square kilometres and is hence the largest shallow endorheic steppe lake in western Europe. The depth of the lake averages at one metre, which results in a well-mixed water column and a high turbidity of open lake waters.

Forty centimetres long soft sediment cores were taken in the open waters of the bay of Rust, which is located at the western shore of Lake Neusiedl. The water body represents an alkaline lake, with elevated pH values differing significantly from those in the sediment: In the sediment cores, alkalinity increases with depth, whereas pH values are distinctly lower than in the lake water column. Major ion distribution reveals an upward diffusion of more saline waters which may be related to a former, more evaporated water body. Microbial activity results in the release of ammonia, phosphate and sulphide, thus contributing to a raise of alkalinity with depth. Redox conditions are anoxic throughout the section, which consists of fine grained, grey carbonate mud that blackens with increasing depth.

Metagenomic analyses of the microbial community composition coupled with pore water analysis, stable isotope measurements, XRD and high resolution imaging investigations will be employed to identify and quantify abundant authigenic carbonate phases and relate their formation processes to microbial activity.

**Talk**

## Carbonate Petrography of sediments along the North West Shelf of Australia (NWS): a contribution to understanding the “oolite problem”

**Maximilian Hallenberger**[1], **Lars Reuning**[1], **Stefan Back**[1], **Stephen John Gallagher**[2], **Hokuto Iwatani**[3]

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Non-skeletal carbonate grains, including peloids and ooids, are regarded as extremely rare in Quaternary sediments located within the Indo-Pacific Ocean. This apparent lack of non-skeletal grains in comparison to Atlantic platforms was termed the “oolite problem”.

Surface-sediment sampling at the distally steepened ramp of the North West Shelf of Australia (NWS) indicates that in this region oolite-rich sediment formed shortly after the Last Glacial Maximum. However, until recently the development and occurrence of ooids further back in time could only be speculated upon. In 2015, IODP Expedition 356 cored the continental margin sequence of the NWS to investigate its depositional history since the middle Miocene. In this study we combine core and geochemical data retrieved from sites U1461 and U1462 with seismic data to analyze the environmental conditions that led to the formation of several intervals rich in non-skeletal grains, which include the oldest recorded Quaternary ooids from the Indo-Pacific region.

Site U1462 displays several horizons that are abundant in well-developed ooids. Ooid-rich sediments are characterized by karstification and high amounts of secondary oomoldic porosity. In comparison, ooids found at Site U1461 are mostly superficial and poorly developed. Porosity is comparatively low with oomoldic porosity and karstic features being absent. This disparity in appearance is thought to be connected to the difference in water depth and platform morphology between both sites. Site U1461 (outer ramp, 127 mwd) could have only reached water depths <5 m, required for ooid formation, during glacial maxima. The time provided for ooid development was therefore most likely limited. Site U1462 (mid ramp, 82 mwd) resided within critical water depths for comparatively longer times during the sea-level lowstands prior to the glacial maxima.

Ooid shoals are thought to have formed during glacials, when elevated aridity led to a high level of carbonate saturation along the NWS. The occurrence of non-skeletal grains at both sites further indicates that ooid formation took place over large parts of the shelf, albeit during different points in time. This implies that ooid-rich sequences cannot be spatially correlated across the shelf.

The data collected and presented within this study reveals that ooids formed in a substantial abundance along the NWS during the Quaternary. This indicates that ooids are probably more common in the Indian and Pacific oceans than previously reported. It further exemplifies that the reservoir quality and spatial extent of ooid-rich sediments may vary significantly depending on the depositional history and shelf position.

**Poster**

## The influence of oceanography and climate as control on Quaternary carbonate sedimentation along the North West Shelf of Australia (NWS)

**Maximilian Hallenberger**[1], **Lars Reuning**[1], **Hokuto Iwatani**[2]

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The widely used “highstand shedding” concept predicts that carbonate production on flat-topped platforms and distally-steepened ramps peak during sea-level highstand when the inner platform is flooded. In contrast, surface-sediment sampling at the distally steepened ramp of the North West Shelf of Australia (NWS) indicates that very little aragonite mud is produced during modern highstand conditions. Instead it has been proposed that considerable amounts of aragonite have been produced during the last glacial maximum forming a regional aragonite lowstand wedge with a volume which could rival typical highstand systems. To test this hypothesis, we investigated the upper 70 m of Site U1461, which has been cored during IODP Expedition 356, using a combination of geophysical log interpretation, thin-section and SEM petrography, stable oxygen and carbon isotope analysis, and XRD derived mineralogy (n>100). XRD data has been further used to calibrate a nearly continuous XRF-Scan, providing a high-resolution record of mineralogical variation (e.g. aragonite).

The investigated section displays a distinct pattern with alternating changes in core color from dark to light. Dark sections are dominated by calcitic mineralogy and elevated amounts of siliciclastics, while the lighter sections are mainly aragonitic with little to no amounts of siliciclastics. Based on composition the aragonite rich sections are further subdivided into parts which are rich in mud and parts which contain high amounts of non-skeletal grains such as peloids and ooids. Ooids, although not well developed, are a clear indication for a very shallow paleo water depth as well as a high carbonate saturation. They are proposed to have formed during glacials, when elevated aridity and a low sea-level guaranteed favorable conditions for ooid formation along the NWS. The first ooid rich section in particular is thought to have formed during the last glacial maximum (LGM), when a large fall in sea-level (-120 m) brought Site U1461 within very shallow water depths.

Crystal morphology, isotope signatures and mineralogical composition of aragonite micrite indicate formation as a seawater precipitate at times of elevated carbonate saturation. Micrite production and redeposition are therefore proposed to have peaked during sea-level lowstands.

During sea level highstands (i.e. interglacials) a combination of strong riverine input, the unimpeded influence of strong oceanic currents, and a low salinity hindered aragonite production. Instead a calcitic pelagic ooze forms, presently overlying the aragonitic lowstand wedge.

Talk

## The geochemical twins Y-Ho, Zr-Hf and Nb-Ta in marine phosphorites

**Franziska Klimpel[1], Michael Bau[1], Katja Schmidt[1,2], Hermann Kudrass[3]**

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Phosphorites are marine chemical sediments composed of carbonate-fluorapatite ($Ca_5[(F,OH,CO_3)/(PO_4)_3]$) and constitute the most important resource for phosphate fertilizer. They incorporate trace elements from ambient seawater and potentially from porewaters, and may be used as archives for trace element and isotope seawater (paleo) proxies. We analysed phosphorite samples from the Chatham Rise off the coast of New Zealand for their trace element composition with a focus on rare earth elements and yttrium (REY) and the geochemical twins Zr-Hf, Y-Ho and Nb-Ta. Geochemical twins are trace elements characterized by identical charges and very similar ionic radii. Hence, the twin pairs show only very minor fractionation in igneous and clastic sedimentary systems and their chondritic ratios (Zr/Hf: 34.3, Y/Ho: 28, Nb/Ta: 17.6) are maintained throughout numerous geochemical processes.

The total REY concentrations in the phosphorite samples range from 80.5 to 260 mg/kg and the shale-normalized ('SN') REY patterns show enrichment of heavy REY compared to light REY, and positive anomalies of La, Gd and Y. The patterns are similar to those of ambient seawater, indicating only minor REY fractionation during REY removal from seawater and incorporation into carbonate-fluorapatite.

The concentrations of Zr (17.5 - 28.4 mg/kg), Hf (0.20 - 0.81 mg/kg), Nb (0.53 - 2.06 mg/kg) and Ta (0.012 - 0.14 mg/kg) are below those of average continental crust, while Y (20.0 - 88.1 mg/kg) and Ho (0.35 - 1.95 mg/kg) are above their respective crustal concentrations. The ratios of the geochemical twins Zr/Hf, Y/Ho and Nb/Ta are super chondritic (34.9-87.9, 38.6-64.9 and 15.3-51.5 respectively). While the Zr/Hf and Nb/Ta ratios also differ from the respective ratio in ambient seawater, the Y/Ho ratio does not. Phosphorites that show seawater $REY_{SN}$ patterns can, therefore, be used as archives for the REY distribution and the Nd isotope composition of seawater. As the Zr/Hf and Nb/Ta ratios found in phosphorites differ from those ratios in potential detritus, Zr, Hf, Nb and Ta in marine phosphorites appear to be derived from ambient seawater. Hence, phosphorites are archives of the Hf isotope composition of seawater, although they do not provide information on the Zr/Hf (or Nb/Ta) ratio of seawater.

Poster

## Axial hybrid event bed development in a pre-collisional low-efficiency turbidite system: the Bordighera Sandstones (NW Italy)

**Pierre Müller[1], Marco Patacci[2], Andrea Di Giulio[1]**

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Increasing studies document that deposits of sediment gravity flows which record evidence of co-genetic laminar and turbulent flow regimes represent an integral part of deep-water clastic sedimentary systems. Such transitional flow behaviour can be explained by turbulence suppression due to modulated detrital clay concentrations arising from erosional entrainment of underlying muddy substrate at both up-dip locations and local distal positions. The resulting facies motif displays a bi- or tripartite arrangement defined by a lower mud-poor sandstone portion and a middle or upper clay-rich, debritic sandstone interval. These deposits (hybrid event beds; HEBs) negatively impact hydrocarbon reservoir properties, as the presence of argillaceous intervals baffles fluid migration. Studies from a wide range of turbidite systems suggest their principal spatial distribution in distal/marginal lobe sub-environments.

A high-resolution stratigraphic dataset has been acquired from the Upper Cretaceous Bordighera Sandstones. The deep-water succession represents a sand-rich elongated turbidite system which – essentially towards its medial and distal domains - becomes heteropic with muddy calcareous turbidites of the Helminthoid Flysch family. Main emphasis was put on the quantification and spatial allocation of inter-sandbody heterogeneity due to HEB development and to contribute to predictive models of HEB distribution. Three main facies groups have been distinguished: (1) clean (i.e. mud-poor) sandstones and microconglomerates, (2) a suite of mudclast-rich sandstones and HEBs and (3) fine-grained sediments. Three main depositional domains - marked by strikingly contrasting dominant lithofacies proportions along a downstream transect - can be recognized. Proximal channel-fill successions are divided from extensive lobate sand sheets by a spatially limited transitional zone of ca. 5 km basin-ward expansion. Whereas the channelized proximal domain represents an array of homogeneous sandstone bodies defined by the dominance of mud-poor facies types, the transitional zone in which the sand fairway lost lateral confinement records a modest increase of bed types proportions accountable for heterogeneity. By contrast, the more distal sheet-like succession is dominated by mudclast-rich sandstones and HEBs, typically distributed in high net-sand packages. A close environmental relationship between meso-scale scouring and enhanced availability of cohesive substrate in the transitional zone is interpreted to control the observed down-dip shift in dominant facies types. Remarkably, the widespread occurrence of HEBs within the high-energy axial zones featuring high sandstone/mudstone ratios and high degrees of amalgamation contrasts models that document HEB distribution to be characteristic of lateral outer fan environments.

**Talk**

## Lost in transition – the selective compaction of a halysitid coral and its implications for diagenesis and time

**Theresa Nohl, Axel Munnecke**

*Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany*

Limestone-marl alternations are reported from the entire Phanerozoic and from various depositional settings. Their rhythmical appearance and their disparity in rock properties are often interpreted as cyclic changes in the depositional environment. The time span for the deposition of a limestone-marl couplet is usually assumed to be somewhere between thousands of years (millennial cycles) and the Milankovitch frequencies (e.g. approx. 20 or 40 ka). We will present data from a halysitid coral (chain coral) from the Silurian of Gotland that indicates a much shorter duration for the formation of such limestone-marl couplets. The specimen is about 30 cm high and is crosscutting several layers of its circumambient limestone-marl alternation. Due to the typical compaction of marl layers ("differential diagenesis") the coral is partly fragmented in these layers, whereas it is well preserved in the limestone. We analyzed thin sections and micro-CT scans to document (1) the spatial extent of the coral, limestone, and marl, and (2) the chronological order of sedimentation and subsequent diagenesis. Our first results confirm a sedimentary infill of the corallum's interspaces while the coral was still alive, which is typical for halysitid corals. Because of the size of the coral colony, this implies a higher sedimentation rate inside than outside the colony. The selective compaction of the coral and the lack of primary aragonitic bioclasts in the marl indicates an early diagenetic aragonite dissolution. Furthermore, the thickness of marl and limestone layers are unchanged between this extreme example inside the fast-growing coral colony and the slowly deposited surrounding limestone-marl alternation, showing the spatial heterogeneity of sedimentation rates. In other words, the age difference between two adjacent limestone layers (separated by marl) in the coral colony is considerably lower than in the surrounding sediment, raising questions about the quality of correlation of single limestone/marl layers in such alternations.

**Poster**

## Analysing the distribution of facies types within Zechstein carbonates of the North German Basin

**Kim Roya Nokar[1], Lars Reuning[1], Stefan Back[1], Philipp Meissner[2], Peter Kukla[1]**

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Here we present Lopingian Zechstein-2 carbonates from a quarry in the southwestern Harz Mountains. They are known to be some of the most prolific reservoir rocks in northern Germany. Facies and mineralogy are the main parameters defining the reservoir quality and are predominantly known from well data to date. This study presents a high-resolution facies model based on outcrop and well data, which offers new insights into the spatial distribution and transitions of facies types.

The studied outcrops represent the majority of the Late Permian, ranging from Zechstein-1 (Werra) copper shale to Zechstein-2 (Stassfurt) Basal Anhydrite. A special focus lies on the Zechstein-2 carbonates. This Stassfurt sequence formed at the southern platform margin of the North German Basin. First analyses of the cores show a shallowing upwards sequence, which was deposited in an intertidal to subtidal environment. In relation to the Werra Anhydrite palaeorelief it can be assigned to an environment in transition from platform to slope, either as part of a highstand systems tract or lowstand prograding wedge.

Further analysis include porosity and permeability measurements of selected core samples, which are supplemented by rock properties derived from spectral gamma ray, magnetic susceptibility and XRD measurements as well as hyperspectral imaging. A detailed thin section analysis of these samples allowed distinguishing the Ca2 facies and subfacies, shedding more light onto the heterogeneous distribution of dedolomitized layers.

**Poster**

## First measurement of a mechanism responsible for enhanced erosion in channel-lobe-transition zones (it is not a hydraulic jump)

**Florian Pohl[1], Mike Tilston[1], Joris Eggenhuisen[1], Matthieu Cartigny[2]**

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On the source-to-sink flow-trajectory, turbidity currents are initially laterally confined by canyon-walls or channel-levees. At some point they lose their confinement and begin to spread laterally, which reduces their capacity to keep sediment in suspension and promotes formation of sediment lobes. However, in some turbidite systems the channels are separated from lobes by a CLTZs, characterized by large fields (10s km) of erosive features such as scours and erosional lineations. Bed morphology suggests that the structure of the unconfined flow in the CLTZ is similar to that of the channel system, rather than the unconfined flow that developed further downstream. As such, there appears to be a lag between the loss of lateral confinement and reorganisation of the current's flow structure of which the latter is hypothesised to play a significant role in creating large-scale scours in the CLTZ.

Here we present the flow structure, along with the erosional/depositional patterns, from experimental turbidity currents in a three-dimensional flume that is divided into a confined and an unconfined section. Sediment suspensions used to generate the currents were held constant, composed of sand (d50: 140µm) with a concentration of 17%(vol.). Downstream variations in the flow field is mapped with an array of ultrasonic-Doppler-profilers and erosional/depositional patterns are mapped using a laser scanner. Results suggest that turbidity currents exhibit a rapid flow collapse upon loss of lateral confinement, and that this flow collapse is associated with a dynamic mechanism that enhances sediment scour and suspension.

The results are the first measurements of a flow mechanism that credibly explains the erosional features often observed in CLTZs. Improved understanding of the formation of CLTZs will improve the reconstructions and interpretations of CLTZs from the rock record as well as the verification of reservoir characterisations of turbiditic deposits close to areas of lateral confinement change.

**Talk**

## Dimensions of submarine lobe elements and their reaction to changing basin settings and flow parameters

**Yvonne Spychala, Joris Eggenhuisen, Mike Tilston, Florian Pohl**

*University of Utrecht, Netherlands, The*

Submarine lobes have been identified within various deep-water settings, including the basin-floor, the base of slope and the continental slope. Their dimensions and geometries are postulated to be controlled by the topographical configuration of the seabed, sediment supply system and slope maturity (disequilibrium/equilibrium). While confinement has been suggested as a main control factor for lobe dimensions in passive and active tectonic settings, it does not explain the spread of lobe dimensions within specific system.

Ten flume experiments were conducted in the 6x11 m Eurotank 3D-flume to study the depositional characteristics of lobe associated with 1) different basin floor dipping angles (0-4°), 2) different sediment concentration of the parent turbidity current (11-19 % Vol), and 3) varying discharge (25 - 40 $m^3$/h). After passing a sand-sculpted preformed channel-levee portion the flows were free to spread onto the unconfined basin floor. Most runs produced lobate deposits that onlapped onto the lower slope independent of basin floor-dip and concentration. We determined that the deposits best describe the hierarchical level of lobe elements. Lobe element length is proportional to basin-floor angle and sediment volume concentration. These boundary conditions also had a strong influence on the overall geometry of the deposits with deposits that show a higher amount of bypass in the proximal area as the basin-floor angles get steeper and concentrations higher. Deposits of runs with lower discharge could be traced higher upslope while runs with lower discharge produced an area of low deposition behind the channel mouth making the discharge the main control factor whether lobe deposits are attached or detached from their channel-levee systems. Flow properties show only subtle differences in initial velocity, shear velocity and height after the break of slope as they can spread freely in an unconfined setting. Integration of measured length values and advection length ($l_a$) calculations show that latter can be used as a first order estimation of lobe element length. However, the estimations are strongly depended on the used average grain size and the method cannot be used to locate the main depocentre. Silt is still deposited after all sand has been deposited in the main lobe element body effectively increasing the lobe element length by approximately four times.

**Poster**

## Miocene to Pliocene reef demise in the Browse Basin, NW Australia - A closer look on the transition to drift deposition

**Sebastian Thronberens[1], Stefan Back[1], Lars Reuning[1], Julien Bourget[2]**

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The upper Miocene to Pliocene interval of the Browse Basin on the Australian North West Shelf (NWS) comprises a significant paleo-environmental change in sedimentary record containing the decay of middle to late Miocene tropical reef build ups buried by drift deposits (Rosleff-Soerensen et al. 2016; Saqab & Bourget 2015). The triggering factors for this transition (e.g. changes in subsidence, eustasy, current regimes, inversion tectonics, climate change) are still discussed and have not been studied in detail. This study focuses on localizing late Miocene to Pliocene reef build ups, analyzing their 3D seismic characteristics and documenting the overlaying drift-deposits. The contribution of differential uplift/subsidence patterns to this transition is quantified applying basin scale 3D backstripping providing a series of incremental paleogeographic reconstructions between the late Miocene to recent. The foundation of the analyses presented is the investigation of a 2D and 3D seismic-reflection data set covering a study area extending over 130.000 km² supported by industry borehole data (logs, cores, and cuttings). SR-Isotope dating, X-Ray diffractometry and microfacies analysis of late Miocene to Pliocene sediments were conducted for 19 boreholes around the region and are integrated with the seismic data, providing rock evidence on stratigraphic change and biostratigraphy. Gamma-ray logging data of over 40 wells are furthermore compared and with core and cutting data enabling subsurface lithology prediction over the entire study area.

**Poster**

## The mid-Cretaceous Debarsu Formation (Upper Albian–Turonian, Khur area, Central Iran): depositional environment, correlation and inter-regional significance

**Markus Wilmsen[1], Marisa Storm[2], Franz Theodor Fürsich[3], Mahmoud Reza Majidifard[4], Felix Schlagintweit[5], Malcolm Hart[6]**

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The up to 600-m-thick Debarsu Formation (Upper Albian–Turonian) in its type area around Haftoman southwest of Khur (Central Iran), has been studied using an integrated approach of detailed logging, bio- and sequence stratigraphic dating as well as facies analysis based on field observations and a detailed microfacies survey. The formation consists of stacked, several tens to a-hundred-metres-thick, basically asymmetric shallowing-upward cycles from grey offshore marls via skeletal-intraclastic limestone with large-scale clinoformed foresets to thick-bedded, bioclastic, occasionally rudist-bearing shallow-marine topset strata capped by palaeo-karsts. The diverse (micro-)facies portfolio (29 facies types) is dominated by bioclastic pack-, grain-, float- and rudstone that reflect deposition on a carbonate ramp (Debarsu Ramp) with a lagoonal shoreline, attached to an elevated semi-arid hinterland in the west and southwest. The outer ramp facies association predominantly consists of microbioclastic marls with open marine microfossils (planktic foraminifera) and fine-grained bioturbated packstone while the mid-ramp facies association is dominated by bioclastic pack- and grainstone (foreset strata). The inner ramp facies association is very varied, mainly comprising high-energy (well washed and cross-bedded) grainstone as well as back-ramp or inter-shoal bioclastic float- and rudist bafflestone. The Debarsu Formation is very widespread in an area west, southwest, and south of Khur (>2,500 km$^2$), but its depocentre was in the type region. The conspicuous shallowing-upward cycles correspond to 3$^{rd}$-order depositional sequences and the sequence-bounding unconformities (palaeo-karst surfaces) in the Upper Albian to upper Lower Cenomanian succession chronostratigraphically correspond to equivalent surfaces known from other Cretaceous basins on different tectonic plates, supporting their eustatic origin. However, a large-scale intra-formational Middle Cenomanian to lowermost Turonian stratigraphic gap in the upper part of the formation must be related to tectonic uplift. The Debarsu Formation corresponds in facies and (sequence) stratigraphic stacking pattern to petroliferous formations on the Arabian Plate (southern margin of the Tethyan Ocean).

**Talk**

## Experimental study on the process of early marine carbonate cementation in sedimentary Halimeda segments

**André Wizemann, Thomas Mann**

*Leibniz Centre for Tropical Marine Research, Bremen, Germany*

Marine cementation of carbonate sedimentary bioclasts is a process that still raises several questions, such as the timescales of cement formation, crystal morphology, mineralogy, and the role of microbes. Consensus is that the development of carbonate cements is driven by the seawater carbon chemistry, which allows precipitation based on the respective carbonate saturation state of the seawater. However, it is uncertain that seawater carbon chemistry alone influences the rapidity of carbonate cementation. For example, the microstructure of sedimentary components may lead to bioclast/component specific progress of cement formation due to the intra-granular morphological microstructure of the carbonate bioclast. Thereby a high intra-granular complexity provides nucleation points that may facilitate a relatively fast cementation of some bioclasts. Sedimentary components that exhibit a very complex intra-granular microstructure are the calcareous segments of the green macro-algal genus *Halimeda*. Thus, these segments may allow rapid development of cements in carbonate-saturated seawater. Here we show early carbonate cementation of sedimentary *Halimeda* segments from a two-year marine laboratory experiment under reef-like conditions. Thin-sections of the segments are investigated with the scanning electron microscope and the digital microscope using cross-polarized light. Additionally, samples from the experiment are compared with sedimentary field samples to characterize the mineralogy and morphology of the carbonate cements. Early carbonate cements that developed in the samples are of the calcium carbonate polymorph aragonite. Sedimentary segments additionally show low-Mg calcite cementation. Different mineralogy of the cements probably develops due to specific hydrogeological settings, freshwater influence or microbial carbonate precipitation. This has implications for any analyses on carbonate bioclasts, e.g. to obtain radiometric ages of single components for the reconstructions of sediment transport and reef island evolution.

**Talk**

## Sea-level controlled back stepping of a large fluvial-dominated delta cycle – An example of the Lower Jurassic of the North German Basin

**Jens Zimmermann[1], Matthias Franz[2], Markus Wolfgramm[1]**

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The successive rise of the global sea-level in the Lower Jurassic contributed to the step-wise flooding of the epeiric Central European Basin and transformation of the enclosed Rhaetian sea (Late Triassic) into a well-connected shelf sea. Large continental-scale rivers draining northern source areas contributed large volumes of sediment to the shelf sea. This study employs geophysical logging data, core data, macro- and micropalaeontology and other data from more than 400 wells in the North German Basin to reveal time-constrained facies reconstructions of the maximum extension (maximum regression) of ancient siliciclastic shallow marine deposits. The focus of this study highlights the interval from the initial transgression in the Early Hettangian towards the remarkably 2nd order flooding in the Early Pliensbachian. The regressive phase in the Planorbis Subchronozone lasted about 0.5 Ma and is characterised by up to 40 m thick progradational and aggradational delta front and delta plain deposits. The reconstructed lobate fluvial delta comprises two main trunk channel systems that fed an upper and lower delta plain of about 20,000 km² each. The regressive phase in the Angulata Chronozone was estimated to about 1 Ma and comprises up to 50 m thick progradational and aggradational delta front and delta plain deposits. The reconstructed lobate fluvial delta comprises an upper delta plain of about 20,000 km² and a lower delta plain of about 15,000 km², dominated by two main trunk channel systems. The about 1 Ma long 2nd order regressive phase in the Turneri Chronozone is characterised by up to 30 m thick aggradational delta plain and subordinately progradational delta front deposits. The reconstructed elongate fluvial delta comprises an upper delta plain of about 16,000 km² and a lower delta plain of about 13,000 km² with one main trunk channel system and abundant interdistributary bays. The regressive phase in the Raricostatum Chronozone is characterised by up to 20 m thick aggradational delta plain and progradational delta front deposits. The reconstructed elongate fluvial delta comprises an upper delta plain of about 12,000 km² and a lower delta plain of about 15,000 km² with subordinate channel systems. Decreasing delta plains, change of delta shape and decreasing trunk channel systems from the Early Hettangian to the Late Sinemurian reflect the stepwise drowning of the NGB during overall sea-level rise.

# 5e,h) Quaternary Geochronology and Earth Surface Processes

Talk

## Evidence for the Early–Middle Pleistocene Transition in Northern Chile

**Ariane Binnie**[1], **Tibor J. Dunai**[1], **Steven A. Binnie**[1], **Pia Victor**[2], **Gabriel González**[3]

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The Early–Middle Pleistocene Transition (EMPT) defines a period during which obliquity driven 41 kyr global climate cycles changed to larger amplitude ~100 kyr cycles. This transition took place over the period between around 1.2 until 0.5 Myr ago. During and after the EMPT, global ice volumes increased and were typified by slower rates of ice build-up, followed by more rapid melting. The geomorphological effects of the longer, more severe, ice ages have left their mark on landscapes throughout the world. In this study, we show that the timing of deep incision and subsequent deposition of large volumes of glaciofluvial sediments in the lower valley of the Huasco River of northern Chile (~28°S) corresponds with the inferred global onset of the EMPT.

Cyclical climate changes play a significant role in controlling the aggradation and incision patterns of rivers and thus climate change and its effects can be revealed by dating river terrace formation. Using cosmogenic $^{10}$Be analysis we dated pebbles on abandoned, well preserved, upper-level fluvial terraces cut into the glaciofluvial sediments of the Huasco River valley of northern Chile (~28°S), approximately 30 km upstream of the river mouth. Twenty-five $^{10}$Be measurements from three separate locations on the uppermost terrace, around 130 m above the current channel, indicate the timing of terrace abandonment was ~1.2 Myr ago, corresponding with the inferred global onset of the EMPT.

The more expansive glaciations that occurred as one of the main consequences of the EMPT would have extended into previously non-glaciated terrain, providing the potential for more erosion and sediment generation and also increased meltwater discharge during deglaciation. The increase in the duration of climate cycles can explain the onset of deeper fluvial incision as well as the presence of the thick sedimentary deposits at the Huasco river-mouth. A key implication of our work is that there were significant amounts of ice in the headwaters of the Huasco catchment within the high Andes, at around 1.2 Myr ago.

Poster

## Holocene Silicic Volcanism at Mt. Erciyes, Central Anatolia, Turkey

**Bjarne Friedrichs**[1,2], **Axel K. Schmitt**[1], **Martin Danisik**[2], **Gökhan Atici**[3], **Esra Yurteri**[3]

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Mt. Erciyes (3917 m a.s.l.) is the highest stratovolcano in Central Anatolia, Turkey. Post-collisional calc-alkaline magma genesis is associated with the convergence of Eurasian, Arabian and African plates and the resulting transtensional stress regime within the Anatolian block. The main edifice of the volcano is located within 20 km of the metropolis of Kayseri with 1.4 million inhabitants, and peripheral lava domes exist within the city's perimeter. As such, Kayseri is a "city on a volcano", but because of limited geochronologic constraints on Mt. Erciyes' eruption ages, the exposure of the Kayseri metropolis to volcanic hazards remains poorly constrained. Here, we report initial results on a comprehensive re-assessment of volcanic hazards of Mt. Erciyes, and present preliminary results of combined U-Th-disequilibrium and (U-Th)/He dating of zircon (zircon double dating, or ZDD) for 16 samples from lava domes and associated pyroclastic deposits.

The ZDD method using U-Th disequilibrium is suitable for the age range of ca. 2.5 to ca. 375 ka, where there are few other dating methods applicable. Older ages can also be determined using U-Pb zircon geochronology in combination with (U-Th)/He methods. The ZDD method yields magmatic crystallization and eruption ages for the same materials, allowing for an independent cross-check for accuracy. Thus, a high-resolution volcanostratigraphy focussing on the late Pleistocene and Holocene volcanic products can be established to identify the eruptive recurrence of the volcanic system, and at the same time resolve magmatic crystallization in subvolcanic magma chambers.

Over the last 75 ka, U-Th disequilibrium rim ages for Mt. Erciyes zircon indicate protracted but intermittent zircon crystallization in a subvolcanic magma reservoir which fed the eruptions of four peripheral silicic domes extending between 5 km south and 20 km north of Mt. Erciyes' summit. Preliminary ZDD ages for rhyodacitic domes Karagüllü, Dikkartın and Perikartın, and dacitic Yılanlıdağ indicate eruptions in the early Holocene. The longevity of zircon crystallization, and the recent, previously unrecognized eruptive activity in the Holocene suggest that magmatic activity underneath Mt. Erciyes persists to the present day. This emphasizes that potential hazards resulting from lava outpouring and associated pyroclastic eruptions, as well as collateral eruptive phenomena like earthquakes and landslides exist despite the fact that historic eruptions of Mt. Erciyes have remained uncertain and contested.

Talk

## Geomorphological, archeological and geological evidence for neotectonic activity on a passive continental margin (Oman)

**Gösta Hoffmann, Alina Ermertz**

*Uni Bonn, Germany*

Neotectonic movement including earthquakes are common on active continental margins and primarily related to subduction processes. Here we report on the passive continental margin of Oman, located on the Northern Indian Ocean. The coastline under study is characterised by a staircase of raised marine terraces of Quaternary age indicating dynamic topography. The geology is dominated by a 2000 m thick sequence of Eocene limestone formations, underlain by a Cretaceous peridotite. Besides the geomorphological indicators there is archaeological evidence for recent earthquake activity. The ancient city of Qalhat – nowadays a protected archeological site - was one of the most important ports situated on the main sea route from India to Persia in the 13th and 14th century AD. Several historical and archeological studies describe the decline of Qalhat as an important trade town, including speculations about destruction by an earthquake in the late 15th century AD. Here we show geological and geomorphological evidence indicating recent tectonic activity along the Qalhat fault, directly underlying the ancient city. Structural analyses prove evidence for neotectonic activity north of Qalhat, movement along the Qalhat fault itself therefore is very likely and the hypothesis that Qalhat was destroyed by earthquake activity is convincing.

We conclude that the processes responsible for neotectonic movement are a combination of forebulge uplift, serpentinisation-driven isosatacy as well as karstification processes.

Talk

## Luminescence dating of Middle-Pleistocene glacial cycles and their implications for hominin presence in Germany

**Tobias Lauer, Marcel Weiss**

*Max Planck Institute for Evolutionary Anthropology, Germany*

We used pIRIR feldspar luminescence methods to establish a chronology for fluvial deposits preserved between the Elsterian- and Saalian tills in central Germany with the aim to obtained information on the timing of both the Middle Pleistocene glacial cycles and early human appearance in central Europe[1].

The luminescence ages illustrate different climatic driven fluvial aggradation periods during the Saalian glacial cycle spanning from 400 – 150 ka. The ages of sediments directly overlying the Elsterian till are approximately 400 ka and prove that the first extensive Fennoscandian ice sheet extension during the Quaternary correlates with MIS 12 and not with MIS 10.

Furthermore, the 400 ka old fluvial units contain Lower Paleolithic stone artefacts that document the first human appearance in the region.

In addition, we demonstrate that early MIS 8 is a potential date for the onset of the Middle Paleolithic in central Germany, as Middle Paleolithic stone artefacts are correlated with fluvial units deposited between 300 ka and 200 ka.

The fluvial units preserved directly under the till of the southernmost Saalian ice yield luminescence age estimates of about 150 ka and show that the southernmost ice-sheet extension during the Saalian glacial cycle into central Germany correlates to a later period of MIS 6.

1. Lauer, T. & Weiss, M. Timing of the Saalian- and Elsterian glacial cycles and the implications for Middle – Pleistocene hominin presence in central Europe. *Sci. Reports 2018 81* **8,** 5111 (2018).

Talk

## Chronological reconstruction of reef island formation in the Spermonde Archipelago, Indonesia

**Thomas Mann[1], André Wizemann[1], Paul Simon Kench[2], Jamaluddin Jompa[3], Hildegard Westphal[1,4]**

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The precipitation of carbonate cements is a rapid process in tropical marine environments. Distinct from calcification, the onset of cementation coincides with the termination of $^{14}C$ uptake within carbonate-sediment forming organisms. Here we show that this relationship presents new opportunities for examining the temporal lag between organism death and deposition in carbonate systems – the prerequisite for reliable depositional chronologies. We dated skeletal constituents collected from discretely stratified reef-island deposits in Indonesia. In each of the strata, internally least cemented segments of the calcifying green alga *Halimeda* yield the youngest ages. Complementary mesocosm experiments on cementation rates reveal that post-mortem cement growth initiates within months after transport commences. Continuous pore-filling cementation promptly stabilizes the initially fragile *Halimeda* skeleton. Furthermore, abrasion experiments show that such cementation significantly increases the durability of segments during transport. Implications of these findings are profound in two respects; first, evaluating residence times of skeletal carbonate constituents based on abrasion features is far from being adequate. Second, the absence of cements within sedimentary *Halimeda* segments signals that post-mortem transport through the intertidal zone occurred quasi-instantaneously. Radiometric ages from such specimens should minimize the temporal lag between organism death and deposition thus making them reliable indicators of sedimentation in supratidal environments.

**Poster**

## Advances in cosmogenic chlorine-36 dating applications

**Silke Mechernich, Raphael Gromig, Tomasz Goral, Steven A. Binnie, Tibor Dunai**

*University of Cologne, Germany*

Cosmogenic chlorine-36 exposure dating is commonly used to investigate the evolution of basalt and carbonate landscapes. However, the community-wide acceptance of chlorine-36 has lagged behind other terrestrial cosmogenic nuclides, in part, because of the multiple production pathways that make the technique so versatile and the chlorine-36 results harder to interpret. Recent work has started to fill in the gaps. In addition to new estimates of production rates and their scaling factors, plus a newly implemented age calculator, we now have the first comprehensive inter-laboratory study for chlorine-36 using two new intercomparison materials (CoCal-N and CoFsp-N). Despite differences in the rock sample preparation and chlorine-36 measurement procedures used in each laboratory, the results of the participating groups agree, highlighting the reliability of the sample preparation and measurement procedures.

However, some points for improvement remain, such as in the reduction of rather high production rate uncertainties for the individual pathways. This accounts particularly for samples with high natural chlorine content, since the uncertainty of chlorine-36 production by epithermal neutron capture is around 24% ($P_f(0)$ = 759 ± 180 n/$g_{air}$/yr, Marrero et al., 2016, QuatGeochron). Uncertainties in the ratio of epithermal neutron production between the subsurface and the atmosphere further increase this issue. Moreover, the handling of snow/moisture cover needs to be explicitly recognised, as it has contrary and depth-dependent effects for the different pathways of chlorine-36 production (Dunai et al., 2014, QuatGeochron). While hydrogen-rich ground cover decreases the spallation process, it increases the underlying thermal neutron flux, which can produce chlorine-36 in amounts that depend on the chemical composition of the rock surrounding the sample.

Here we present examples of chlorine-36 carbonate dating of moraines, alluvial fans, earthquakes, and bedrock exhumation. For these applications we use different sampling methods (boulder samples, bedrock samples, depth profiles) and test different parameters in the available age calculators. We discuss the reliability, robustness and pitfalls of the results to allow a realistic impression of the capabilities of this dating method.

**Talk**

## Using cosmogenic nuclides to trace a steep climate gradient over a short distance in hyperarid northern Chile

**Joel Mohren, Steven A. Binnie, Damián A. López, Benedikt Ritter, Tibor J. Dunai**

*University of Cologne, Germany*

Long-term and persisting aridity has preserved an almost relict landscape in northern Chile. Thus, the region provides excellent conditions for the study of paleoclimate and the impact of climate and climate change on Earthshaping processes and topography formation. Here we present a set of catchment-wide denudation rates along a short W-E transect on the northern rim of the Río Loa Canyon in the Coastal Cordillera of northern Chile (latitude 21.4ºS). In the study area, a flat sedimentary surface consisting of unconsolidated conglomerates of Miocene age becomes increasingly dissected and changes into a badland-like topography within a few kilometers of distance. We derived the denudation rates from cosmogenic $^{10}$Be in amalgamated samples from channel quartz pebbles. The denudation rates increase from east to west within ~3 km of distance, indicating the presence of a steep time-integrated climate gradient in this area. When related to major geomorphologic parameters, the denudation patterns point towards the presence of two different erosional regimes, which are sharply bounded against each other, separating a detachment-limited erosion regime in the western portion from a transport-limited regime to its eastern portion. Only the westernmost catchments show signs of sub-recent discharge. The gradient in landscape modification by fluvial activity evolved over multiple stadial/interstadial cycles. It is likely that the development of the observed geomorphic gradient is accelerated during wetter periods, such as during stadials, when wetter zones shift northward (Lamy et al. 2000, Terra Nova 12(1), 8-13). To test this hypothesis we measure in-situ cosmogenic $^{14}$C in the pebbles to distinguish between long-term Quaternary ($^{10}$Be) and Holocene ($^{14}$C) denudation rates.

**Poster**

## Towards a reconstruction of landscape developments in the Otterbach catchment (Bavarian Forest, Southern Germany)

**Sebastian Scheck[1], Lydia Krauß[1], Daniel Schwindt[1,2], Jörg Völkel[1]**

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In the scope of the TUM-CZO (TU-Munich Critical Zone Observatory), the Otterbach Valley has been focus of numerous research approaches. Those investigated soil carbon dynamics, hydrological processes, and landscape developments. Aim of the presented study is the reconstruction of landscape evolution in the Otterbach catchment due to anthropogenic land use and natural process dynamics. The Otterbach (western Bavarian Forest, Germany) is a creek of 2nd stream order and runs directly into the Danube River. Alluvial and colluvial sediments have been investigated since they are generally regarded to be correlated to anthropogenically induced erosion. Sedimentological analysis of soil pits (up to 2 m depth) and core samples (up to 18 m depth) and geophysical measurements (electrical resistivity tomography and seismic refraction tomography) have been applied to characterize the shallow subsurface. Radiocarbon dating was used for the chronostratigraphic context. Clay curtains have been visible within the slope sediments almost continuously up to 18 m depth. Those can be interpreted as a result of illuvial processes and subsequently, suggest continuous genesis during former Interglacial phases. During the Late Glacial and the Early Holocene stronger erosional processes occurred. Radiocarbon dates of alluvial floodplain sediments point to smaller sedimentary relocation processes between around 2.400 and 1.000 BP. The results indicate that the development of recently given alluvial floodplains is partly due to anthropogenically induced erosion in the region.

**Poster**

## Postglacial evolution of large fan systems in the Upper Rhone Valley, Switzerland

**<u>Anna Schoch</u>[1], Jan Henrik Blöthe[1], Henry Munack[2], Jens Hornung[3], Alexandru Codilean[4], Réka Fülöp[4], Lothar Schrott[1]**

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In the European Alps, where slopes adjust to postglacial conditions, the evolution of large fan systems has important implications for natural hazard assessment and for understanding postglacial landscape development. In the Upper Rhone Valley, Switzerland, three large fan systems (footprint area ~1 km$^2$ each) are fed by similarly sized catchments. Grounding on three different methods, geomorphometric analysis of high-resolution digital topography, geophysical surveys (GPR & ERT), and surface exposure dating using cosmogenic radionuclides, we seek to analyze 1) the morphology of the fans and its feeder basins, 2) the sedimentary facies and architecture of the deposits, and 3) the chronology of the events that lead to the formation of the fans.

The sediment source regions for the three fans, all coming down from the northern valley flank, are well defined, mainly consisting of gneissic lithologies. Based on morphometric analysis, we estimate the eroded volume from the feeder catchments to range between 50 and 62 x $10^6$ m$^3$, translating to minimum uniform denudation rates of ~5-6 mm yr$^{-1}$ averaged over 15 kyr (when deglaciation exposed the valley), outranging $^{10}$Be-derived denudation rates from adjacent catchments by factor 2 to 15. Ground penetrating radar surveys (> 10 km length), measured with 40 and 200 MHz antennas, clearly identify levees and channels intercalated with large boulders near the surface, pointing towards high-magnitude debris flow events. Deeper below the surface, GPR results point to larger blocks that lack a fluvial signature, rather indicating catastrophic deposition below the debris-flow dominated cover. These findings are supported by ERT surveys, drillings on the margin of one of the fans, as well as a series of m-sized subangular boulders covering parts of the fans. Using cosmogenic nuclide abundances, the exposure age of these large boulders as well as the exposure ages of bedrock outcrops within the feeder catchment were determined to establish a chronology of fan generation. Exposure ages in the catchment range dominantly between 5800 and 6000 a BP with single ages dated around 3900 and 1100 a BP. Boulders exposed at the surface of the fan exhibit ages between c. 800 and 4500 a BP. These results indicate that fan formation took place over several thousands of years during the Holocene. However, these result suggest that the catchment was already formed 6000 a BP. Settlements on the fan (14$^{th}$ century) and a minimum age of c. 830 a BP indicate geomorphic activity ceased several hundred years ago.

**Poster**

## Biotic control on sediment dynamics mediated through grain size distribution in the Chilean Coastal Cordillera

**<u>Simon Terweh</u>, Thomas Hoffmann, Lothar Schrott**

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Earth surface processes in natural environments are controlled by tectonics, climate and Biota. While the effects of tectonics (increasing topography and controlling lithology) and climate (controlling physical weathering and runoff generation) often show a clear trajectory, the effect of vegetation is more ambiguous. On short timescales vegetation reduces hillslope erosion and sediment transport by trapping and stabilisation. This is counterbalanced on longer timescales by enhanced biochemical weathering and the production of fine grained material on hillslope soils. We state that the grain size distribution (GSD) of sediments supplied to the fluvial system is a key factor, since it exerts a strong control on transport mechanics and morphodynamics in the river system which in turn control incision and deposition and hence landscape evolution.

To investigate vegetation induced shifts in GSD, we collected about 75 bulk samples of hillslope and channel sediments in four granitic mountain headwaters in the Coastal Cordillera of Chile. These headwaters are located along a bioclimatic gradient from arid, non-vegetated catchments in the north to humid and densely vegetated catchments in the south. By sampling hillslope and fluvial sediments from the hilltop to the channel outlet we track the spatial variability of GSDs along the sediment flow path under different degrees of biotic activity.

Results show a weak variability of the GSD in the arid catchment contrasted by a much stronger sorting of grain sizes in the more humid catchments, where fine grained hillslope samples are accompanied with coarse grained fluvial sediments. Along the transport path a vegetation-induced fractionation of sediment transport into a faster fine and a slower coarse grain component is visible in the more humid catchments, which can be addressed to a higher effectivity of transport, when the finer material is delivered to the channel. The degree of amouring found in the channel surface sediments furthermore indicates a stronger size selectivity and supply limitation in the more densely vegetated catchments.

**Talk**

## Fault activity, tectonic segmentation, and deformation patterns in the western Himalaya on geological timescales inferred from landscape morphology and thermochronology – a summary

**Rasmus C. Thiede[1,2], Bodo Bookhagen[2], Dirk Scherler[3,4], Saptarshi Dey[5], Patricia Eugster[2], Markus Nennewitz[2], Edward Sobel[2], Konstanze Stübner[2], Ramon Arrowsmith[6], Vikrant Jain[5], Manfred Strecker[2]**

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The distribution of tectonic activity in the Himalaya has been debated for decades and several aspects remain unknown. For instance, the amount of crustal shortening that ultimately sustains Himalayan topography and the activity of major fault zones remains poorly quantified over geological-timescales. In our work, we study landscape morphology and combine surface exposure and thermochronologic dating methods with models to address the spatial and temporal pattern of deformation in the western Himalaya. Of particular interest is a 30 to 40-km-wide orogen-parallel belt of rapid exhumation that extends from central Nepal to the western Himalaya. This belt has been linked to a mid-crustal ramp in the basal décollement, to out-of-sequence basement thrusts, and to the growth of Lesser Himalayan duplex structures.

From our results we conclude that all major deformation zones in the western Himalaya are active and some portion of crustal shortening is accommodated by active out-of-sequence faulting sustaining topography, despite rapid erosion. We have published several new studies containing new apatite fission-track and zircon U-Th/He cooling ages from the western Himalayan region, particular in the vicinity of the transition from the central to the western Himalaya (~77°-78°E). We analyzed the spatial distribution of the relative change of river steepness using averaged basin wide river steepness indexes ($k_{sn}$) from both along and across strike to gain information about the regional distribution of differential uplift patterns and to relate this to the activity of distinctive fault segments. Our results indicate the existence of three orogenic segments with distinctive landscape morphology, structural architecture, and fault geometry along the western Himalaya: Garhwal-Sutlej, Chamba, and Kashmir Himalaya (from east to west). We observe a positive correlation of averaged $k_{sn}$ values with long-term exhumation rates. derived from recently published regional thermochronologic datasets combined with thermal modelling as well as with millennial timescale denudation rates based on cosmogenic nuclide dating. Moreover, our data recognize distinctive fault segments, suggesting varying differential uplift along the strike of the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT), and in the vicinity of the steep topographic transition between the Lesser and Greater Himalaya. In this region, we relate out-of-sequence deformation along major basement thrust ramps such as the Munsiari Thrust (MT) combined with deformation along mid-crustal ramp along the basal décollement as the main driver of exhumation along the southern Himalayan front. This implies that some portion of crustal shortening is accommodated here on Quaternary if not longer timescales.

# 5f) Integrated chemostratigraphy and applications

Talk

## The challenge of correlating condensed and patchy sections by using a multi-approach method: Integrated results from Upper Cretaceous epicontinental shelf (Münsterland Cretaceous Basin, Germany)

**Michaela Berensmeier[1], Bettina Dölling[2], Christian Linnert[3], Markus Wilmsen[1]**

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The calibration and correlation of proximal shallow-water deposits are demanding tasks due to the high grade of condensation and the patchy nature of the stratigraphic record. Stratigraphic signals can be altered or even be lost; and thus the correlation to intra- and inter-basinal standard sections can be hampered. Three fully-cored boreholes including Cenomanian–Coniacian strata from the southwestern margin of the Münsterland Cretaceous Basin (MCB, northwest Germany) are the basis of the present case study. The sections have been stratigraphically calibrated and correlated by using an integrated approach of bio- (mainly calcareous nannofossils), chemo- (carbon-stable isotopes) and sequence stratigraphy as well as geophysical borehole data (natural gamma radiation). Glauconitic lime- and sandstones (greensands) as well as clayey-silty marls and spiculitic marly limestones with shallow marine biota comprise the studied lithologies indicating a proximal epicontinental shelf setting. The lithostratigraphical units are assigned to: Essen Grünsand Formation, Büren Formation, the Bochum-, Soest- and Mülheim-Grünsand members of the Duisburg Formation as well as the Emscher Formation including its greensand member. Biostratigraphy is based on calcareous nannofossils and led to identification of biozones UC1–3 and UC6–10 including a potential gap in the latest Cenomanian (absence of biozones UC4 and UC5). Sequence stratigraphical investigations revealed eight 3$^{rd}$-order sequence bounding unconformities (SB): Cenomanian (Ce) SB Ce 2–5 and SB Turonian (Tu) 1–4, dividing the strata into depositional sequences (DS) DS Ce 2–5, DS Ce–Tu 1 and DS Tu 2–4. The depositional sequences are stacked into two 2$^{nd}$-order cycles separated by SB Tu 1 (Lower/Middle Turonian boundary interval). The carbon-stable isotope data of the less condensed drill core have been correlated to the Cretaceous standard section for northwest Europe (Dover) and the regional standard of the southern MCB (KB Anröchte/Werl). Several Cenomanian–Turonian isotope events have been recognised, e.g. the oceanic anoxic event 2 expressed as a major positive isotope excursion. Eustatic sea-level changes affected the MCB and function as main driver of facies and stratigraphical architectures, supported by the correlative nature of depositional sequences and their bounding unconformities. The multi-approach method of stratigraphical analyses presented herein led to a better understanding of spatio-temporal depositional patterns and sea-level dynamics at the margin of a Late Cretaceous epicontinental sea.

Talk

## A high-resolution continental case study of orbital and solar forced environmental changes during the Early Danian Dan-C2 hyperthermal

**Alena Ebinghaus, David Jolley, David Kemp**

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Hyperthermal events represent phases of rapid global warming in Earth's history, and are commonly associated with the transfer of large amounts of $^{12}C$ enriched carbon (C) to the ocean and atmosphere systems, preserved as a pronounced negative carbon isotope excursion (CIE) in the rock record. Despite major advances in past climate studies, our understanding of the complexity of continental system responses to ancient climate warming is little constrained.

To enhance our understanding of the impacts that hyperthermals have had on continental sedimentation and ecosystem dynamics, we investigated the lacustrine succession deposited in the late Cretaceous Boltysh meteorite impact crater (Ukraine). The sedimentary fill of this crater contains evidence for a CIE identified as the Early Danian Dan-C2 hyperthermal event (c. 65 My). A borehole (Hole 42/11) drilled in the central part of the Boltysh crater provides an excellent record of this CIE in finely laminated lacustrine sedimentary deposits.

A combination of bulk organic C-isotope, palynological and sedimentological examinations has yielded a detailed record of the lake environment through the Dan-C2 event at a resolution analogous to modern lake sediments. Cycles in C isotopes, palynofloral and lithostratigraphical changes suggest the presence of 21 ky precession-scale orbital forcing. Moreover, there is also evidence for shorter-term solar forcing in plant ecology and lake dynamics through the increasingly drier climate associated with the CIE (~2 ky Hallstatt, ~200 y DeVries-Suess, and ~11 y Schwabe cycles).

Our analyses suggest that sedimentological and plant ecological responses to climate warming at the onset of the CIE was transient rather than rapid. Orbital to solar-scaled climate oscillations, together with crater morphodynamics overprinted the potential environmental impact of the CIE. By contrast, the changes in the vegetation community correspondent to precession-scale cycles across the CIE indicate rapid shifts, likely related to ecological resilience within an increasingly stressed regime as a consequence of precession-scale climate change (=moisture availability oscillations, MAOs). Sedimentary facies and lake level fluctuations in correlation with the MAOs are interpreted to reflect intensified hydrological and climatic response linked to the CIE. This study provides an excellent case study to characterise the complexity of response patterns and rates of climate warming on a local system scale, and emphasizes the need for comparable studies to better understand the lateral and temporal variability of Earth's system response on the continents.

**Poster**

## Variations in the mineralogical composition of impure rock salt successions (Rotliegend, Zechstein, Keuper) from the North German Basin - first results

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Salt rocks with higher amounts of detrital impurities of smaller grain sizes are commonly referred to as salt clay or argillaceous rock salt. The North German Basin provides a broad variety of those impure evaporitic successions that were deposited from late Paleozoic through middle Mesozoic times. This study shows the variations in mineralogical compositions that can be expected in different types of rock salt. Knowledge about the type and content of detrital phases is crucial both in order to understand the genesis of evaporite successions as well as to pre-estimate how impurities of different types might affect the technical use of rock salt such as solution mining or long term storage of radioactive waste.

This study covers the investigation of impure rock salt from Rotliegend, Zechstein (Leine and Aller succession) and Keuper successions, which represent different settings of evaporite genesis from marine epicontinental basin (Zechstein) to continental playa environment (Rotliegend and Keuper). Results were generated from the study of thin sections, XRD analyses on insoluble phases and inductively coupled plasma optical emission spectroscopy (ICP-OES) on soluble phases like halite and anhydrite.

Differences in the depositional environment can both be seen from variations in bromine content in halite as well as in the dominance of either magnesite or dolomite in the carbonate mineral content.

The siliciclastic fraction of the studied successions shows common mineral phases like quartz, feldspar, muscovite and chlorite being present in all rock salt types. Differences are observed in the comparison of feldspar and clay mineral content in the studied salt successions. While for example Rotliegend rocksalt contains significant amounts of detrital plagioclase as well as detrital muscovite and chlorite, Zechstein rock salt shows a greater variety of clay minerals that account for up to 40-60 wt. % of the total insoluble phase. Clay minerals typically associated with halite successions such as talc and koenenite are absent in the studied rock types.

Differences in mineralogy show that the composition of impurities in rock salt is largely dependent on the terrestrial input as well as the depositional setting. Those differences should be taken into account and further analyzed when assessing different types of salt rocks for technical use. Moreover the knowledge about differences in primary clastic input into a salt basin can lead to better understanding of salt stratigraphy as well as for possible local metamorphism inside salt structures.

**Talk**

## Integrated stratigraphy of an offshore environment influenced by intense siliciclastic supply: implications for Coniacian tectonosedimentary evolution of the West Sudetic area (NW Bohemian Cretaceous Basin, Czech Republic)

**Roland Nádaskay[1,2], Yulia V. Kochergina[1,3], Stanislav Čech[1], Lilian Švábenická[1], Jaroslav Valečka[1], Bohuslava Čejková[1]**

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Integrated stratigraphic research focused on the lower–middle Coniacian interval recorded by the borehole 4650_A Skalice, NW-part of the Bohemian Cretaceous Basin (BCB). It comprises a ca. 175 m predominantly mudstone sequence bracketed by sandstones deposited in deltaic/nearshore environment (Uličný et al. 2009). Two lithofacies groups were distinguished: 1) unconfined beds of calcareous mudstones to siltstones, locally with sand admixture; 2) gravity-flow deposits, represented by heterolithic facies, an irregular alteration of mudstones and thin beds of sandstones, and by isolated upward-fining sandstone intercalation.

Biostratigraphy was employed to resolve stratigraphic subdivision of the monotonous mudstone succession due to absence of lithostratigraphic markers. Lower Coniacian strata were determined by inoceramids *Cremnoceramus walterdorfensis hannovrensis (Cwh)* and *C. crassus inconstans (Cci)* ca. 20 m above the top of underlying Turonian–Coniacian sandstones. Concerning nannofossils, a quantitative rise of *Marthasterites furcatus* was observed below the occurrences of *Cwh* and the appearance of transitional forms *Quadrum-Micula* was recorded above *Cci*. Top of the *Cci* zone marks the boundary of genetic sequences CON 1 and 2. Timespan of CON 2 sequence is defined by the extent of the *C. crassus crassus (Ccc)* zone that corresponds to the upper part of marker beds (silicified limestones) in the axial part of the BCB. The scarce presence of the nannofossil *Micula staurophora*, UC10 zone, was recorded between the last occurrence (LO) of *Ccc* and the FO of *Inoceramus frechi* and indicates the base of middle Coniacian. Element proxies (Si/Al, Ti/Al, Zr/Al) are lithology-dependent. They reflect subtle variations of coarser siliciclastic input into low-energy setting, mostly by action of gravity currents, interpreted as hyperpycnal.

Macroscopic fossil finds were selected for Sr-C-O isotopic analyses. The isotopic composition of carbonate phase of studied suit is variable. Strontium isotopes range from 0.707353 to 0.708271; $\delta^{13}C$ and $\delta^{18}O$ values are -2.6 –3.0‰ $_{PDB}$ and -9.7 – -1.6‰ $_{PDB}$, respectively. Sample of inoceramid bivalve (361.2 m) and carbonate fraction of surrounding rock have similar isotopic composition, with $^{87}Sr/^{86}Sr$ =0.707926, $\delta^{13}C_{carb}$.= 1.1 ‰$_{PDB}$, $\delta^{18}O$=-3.9‰$_{PDB}$, and $^{87}Sr/^{86}Sr$ =0.708110, 1.4‰$_{PDB}$, and -4.5‰$_{PDB}$, respectively. The sandstones (294.85 m) show radiogenic Sr composition ($^{87}Sr/^{86}Sr_i$= 0.713445). Based on comparison with published Coniacian Sr-isotope ratios (e. g. Steuber 2001, Frijia et al. 2015), and major/trace elements and isotopic composition we assume that samples were affected by several processes such as: reaction with meteoric water, continental source contamination (by siliciclastic material delivered from West Sudetic island) and structural alteration.

Talk

## The use of XRF chemostratigraphy to develop a sequence stratigraphic framework for the mudstone-dominated Lower Cretaceous succession in the eastern Lower Saxony Basin, Northern Germany

**Hauke Thöle[1], Ulrich Heimhofer[1], André Bornemann[2], Jochen Erbacher[2,3], Friedrich Wilhelm Luppold[4]**

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Delineation of sequences and their component systems tracts in mudstone-dominated successions is challenging due to the relatively homogenous, fine-grained nature of the strata. We used high-resolution elemental intensity data from X-ray fluorescence (XRF) core scanning in order to develop a sequence stratigraphic framework for the Lower Cretaceous monotonous mudstone succession in the eastern Lower Saxony Basin (LSB) of Northern Germany. The study is based on four drill cores covering the Berriasian to Aptian interval of the LSB. Carbon isotope analyses of bulk organic matter ($\delta^{13}C_{org}$) as well as grain-size and $CaCO_3$ content measurements were additionally carried out on discrete samples. The studied cores representing both proximal and distal environments of the eastern LSB can be correlated accurately by utilizing cyclical variations in selected XRF elemental ratios. The additive log ratio of K/Ti has proven to be particularly suitable in this regard. The inter-core correlation shows clearly that chemostratigraphic variability within the studied succession is laterally reproducible at local scales and can be correlated across the eastern LSB. In general, measured XRF elemental profiles reveal a high degree of geochemical variability, and the additive log ratios Si/Al and Ca/Ti have been used to characterize the studied cores in terms of variation in grain-size and $CaCO_3$ content, respectively. Vertical textural (grading) trends inferred from Si/Al changes were used to identify transgressive and regressive episodes within the mudstone-dominated succession. Large-scale upward-fining intervals (decreasing Si/Al ratios) are used to define transgressive systems tracts (TSTs) and the level at which the stacking patterns change from upward-fining to upward-coarsening as maximum flooding surfaces (MFSs). Conversely, large-scale upward-coarsening packages (increasing Si/Al ratio) are interpreted as regressive systems tracts (RSTs) and the tops of these coarsening-upward trends as maximum regressive surfaces (MRSs). Our results are generally in agreement with previously recognized transgressive-regressive trends in the LSB and adjacent areas. This clearly shows that systematic geochemical variations recorded in mudstone-dominated basinal settings are suitable to establish sequence stratigraphic frameworks.

Talk

## Integrated stratigraphic dissection of the Upper Albian to Lower Turonian of Esfahan (Iran): elucidating the enigma of the Glauconitic Limestone

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The so-called Glauconitic Limestone of Esfahan is renowned for its Late Albian to Middle Cenomanian ammonite faunas. It is a very conspicuous, albeit thin (<4 m) lithologic unit that consists of two genetically unrelated stratigraphic portions. The lower part of the unit comprises fine-grained, weakly to moderately glauconitic and poorly fossiliferous limestones that rest with a minor discontinuity on deep-marine shales of the mid-Upper Albian Bazyab Formation. Micro- and macrobiostratigraphic evidence suggests that these strata are mid-Late Albian in age. The upper part of the unit consists of a fossiliferous Glauconitic conglomerate with rounded limestone pebbles, cobbles and boulders as well as phospatized bio-/lithoclasts in a strongly glauconitic-bioclastic matrix, yielding the well-known Late Albian to Middle Cenomanian ammonite faunas of the Glauconitic Limestone. The Glauconitic conglomerate has a major erosional unconformity at its base, truncating the lower part of the Glauconitic Limestone on short distances and showing a fining-upward trend into the overlying organic-rich marls and argillaceous limestones. Planktic foraminifers date the matrix of the upper part of the Glauconitic conglomerate as upper *Rotalipora cushmani* Zone (mid-Late Cenomanian) while the overlying fine-grained offshore deposits yielded latest Cenomanian to early Turonian foraminifers, ammonites and inoceramid bivalves. The carbon stable isotope curve up-section of the base of the Glauconitic conglomerate shows the conspicuous structure of the major positive excursion of the oceanic anoxic event (OAE) 2 and serves as precise instrument for the high-resolution chemostratigraphic calibration of the Iranian sections. In a nutshell, the Glauconitic conglomerate is a complex, condensed transgressive lag onlapping a palaeo-landscape resulting from late Middle to early Late Cenomanian tectonic uplift. The Late Albian to Middle Cenomanian phosphatized ammonites from the bed are derived, i.e., are typical remanié faunas. The offshore deposits overlying the Glauconitic conglomerate indicate a considerable deepening in response to a major eustatic sea-level rise and highstand across the Cenomanian–Turonian boundary associated by increased organic carbon burial related to the OAE 2. The Esfahan area thus provides a new reference section for the OAE 2 in the Middle East.

Poster

## The Cenomanian–Lower Coniacian (Upper Cretaceous) of the south-eastern Münsterland Cretaceous Basin, Germany: integrated stratigraphy, facies development and correlation

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The integrated sedimentologic and stratigraphic analyses (based on litho-, bio-, event, chemo-, gamma ray and sequence stratigraphy) of two new core sections greatly improved the understanding of sea-level changes, facies development and correlation of the lower Upper Cretaceous succession in the south-eastern Münsterland Cretaceous Basin. Detailed carbon stable isotope curves allowed calibrating the successions on intra- and interbasinal scales. Sedimentary unconformities (sequence boundaries), marker beds (mainly marl layers) and volcanic ash layers (bentonites) turned out to be isochronous within the chemostratigraphic framework. The identification of Turonian bentonites greatly improved the understanding of the stratigraphic relationships, especially in the Upper Turonian, while correlation of natural gamma radiation logs turned out to be a valuable intrabasinal tool. A superordinate second-order sea-level cycle is mirrored by the increasing significance of distal facies and thicknesses of depositional sequences, reflecting the rise of accommodation space during the Cenomanian–Early Turonian. This trend started to become reversed in the mid-Turonian and the cycle is terminated at a major unconformity at the base of the Soest Grünsand Member of the Duisburg Formation in the mid-Upper Turonian. Condensation of the mid- and uppermost Turonian documents the lack of accommodation during a phase of second-order lowstand, followed by retrogradational facies development during the Early Coniacian, marking the transgressive limb of a new second-order cycle. Sequence boundaries in the Cenomanian–Turonian successions provide evidence for third-order sea-level fluctuations superimposed onto the first early Late Cretaceous second-order cycle. They match sequence boundaries SB Ce 1–5 and SB Tu 1–4 known from Central European basins (and elsewhere), supporting eustatic sea-level changes as their drivers. The sea-level fall reflected by unconformity SB Tu 4 in the Upper Turonian is of major magnitude and the overlying mid-Upper Turonian Soest Grünsand Member is the only level of greensands in the Upper Turonian of the south-eastern Münsterland (the “Alme Grünsand”, coined for another, allegedly uppermost Turonian greensand level, does not exist). In conclusion, the new sections provide an excellent standard for the lower Upper Cretaceous in the south-eastern Münsterland Cretaceous Basin.

# Topic 6: Neotectonics, earthquakes, impacts and natural hazards

## 6a,c) Natural hazards: earthquakes, tsunamis, landslides | Sea-level fluctuations over time – Sea-level index points and dating approaches

Poster

### Stratigraphic Control on Seismic Behavior in the Vicinity of Kalabagh Fault, Sub Himalayas, Pakistan

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The Sub Himalaya in Pakistan comprises of the Salt Range and Trans Indus Ranges creating the Kohat Plateau, the Potwar Plateau and the Bannu Basin. The Pre-Cambrian Salt Range Formation is a reason for salt tectonics in both Kohat and Potwar Plateaus. Additionally, the Kohat Plateau in the west is characterized by the Eocene Bahadur Khel Salt which is absent in the Potwar Plateau in the east. Detachment along the Bahadur Khel Salt generated the roof thrusts while decollement along the Salt Range Formation mark the floor thrusts of duplex structures in the Kohat Plateau. This distinguishes the Kohat Plateau from the Potwar Plateau. In this study, seismic events from the USGS earthquake catalog from 1950 to present are analyzed to get an overview of seismic behavior of the area related to the stratigraphic record on both sides of the Kalabagh fault. Data is collected from the USGS catalogue with earthquake magnitudes ranging from 4.5 to 6.3 on the Richter scale in the east and west of the Kalabagh fault. These earthquakes are mostly distributed on the eastern Potwar Plateau, while no significant earthquake is recorded in the western Potwar Plateau. Seismic activities are also recorded in the Kohat Plateau i.e. the north of Surghar range with a maximum 6.3 magnitude earthquake in 1992. Depths of these earthquakes varies from 16 to 37 kilometers and recurrences rates of 10 to 12 years in the Kohat Plateau in different localities. These seismic activities in the Kohat Plateau show on going compression on western side of the NNW trending right lateral Kalabagh strike slip fault which have an offset of more than 100 kilometers. This compression is causing moderate seismic activities in the north of the Surghar Range. Earthquake data in the Eastern Potwar does not show significant activity along the Salt Range thrust, instead it shows some activity in the north of Karangal-Diljaba Thrust with recurrence rates of 5 to 10 years and depths ranging 30 to 50 Km for 4.5 and above magnitudes. This shows accumulation of energy due to SE-NW compression along Salt Range Thrust as InSAR and GPS based studies show uplifting of 3 to 10 mm per year in the Potwar Plateau. Higher uplift rates in the western Potwar coupled with no seismic activity in the past years are indicative of stress accumulation along the Salt Range thrust in the western Potwar Plateau.

Talk

### Organic-geochemical characteristics of 2011 Tohoku-Oki tsunami deposits in northern Japan

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Wide coastal areas of the main island of Japan, Honshu were affected by the March 11th, 2011 Tohoku-oki tsunami. Besides the destruction by the 9.1 $M_W$ earthquake itself, the tsunami caused further devastating damages and loses of lives, while leaving behind sandy and muddy deposits up to 4.5 km inland. However, not only sediment was transported inland and distributed over the coastal plain, but as well biological and anthropogenic organic chemicals associated with organic material in the sediments or mobilized by the destruction of factories and plants of any kind were transported and deposited with the tsunami deposits. These organic compounds give the tsunami deposit an unique geochemical character that is detectable and distinguishable from sediments former and following to the tsunami event.

In an extensive, multi-proxy study we successfully applied organic-geochemical analyses on cores from several field sites along the central and northern coastline of Honshu, Japan. Using this approach, we were able to identify compounds and characterize the organic-geochemical signature of the tsunami deposit at each individual field location. In connection with grain size and micropaleontological data, organic-geochemical analyses, especially of anthropogenic markers (such as polycyclic aromatic hydrocarbons, pesticides and halogenated compounds), can contribute and extent our understanding of mechanisms during tsunami events and help to identify tsunami deposits even behind the sandy deposition limit of event horizons. Therefore, we present our current findings and our latest data, as well as giving an overview of the achievements of this new application for tsunami investigations.

Poster

## Holocene landscape change of the coastal area of NW Germany – Mapping and first chronology of prehistorical storm surge layers

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The overall landscape history of the NW German coast is characterized by the Holocene sea level rise. Furthermore, the event triggered changes of the coast should not be underestimated. In this study we focus on pre-historical storm surge sediments within the coastal Holocene of NW Germany.

The impact of pre-historical storm surges on the paleogeography is expected to be completely different from the historical storm surges due to a natural landscape without dikes and therefore natural sedimentation processes in the coastal area. For the East Frisian German North Sea coast the spatial extent of pre-historical storm surge deposits has not been documented or analysed so far. Although geoscientists studying the coastal Holocene know typical storm surge layers from several locations, these layers have never been mapped systematically or correlated so far.

The question arises how intensively storm surges influenced the landscape in pre-historical times: How far and how strong did the water inundate the hinterland? From what time onwards storm surge layers can be detected between Ems/Dollart and Weser Estuary? Can we correlate pre-historical storm surge sediments along the coast? Did storm surges trigger transgressions which have been originally correlated to increased sea level rise?

To approach these questions we focus on mm to cm thick clastic seams within peat horizons in the sedimentological record of the Holocene coastal sediments. They are related to the so called 'Klappklei' phenomenon, describing a postsedentary event in a peat cliff situation. During severe storms the upper part of the peat is being uplifted, fine grained clastic material is deposited and fixed within the peat when the upper part is settling again after the storm. Therefore, the 'Klappklei' layers are a well detectable archive of storm surge history along the coast.

Based on (i) the LBEG (Landesamt für Bergbau, Energie und Geologie) archive core database comprising several thousand cores for the coastal Holocene between the Dollart-Ems and the Weser estuary, (ii) paleolandscape reconstructions and (iii) the relative sea level curve for the Eastfrisian coast, we will show distribution maps of storm surge layers and develop a first chronology of pre-historical storm surge sediments.

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Bruns, I., Bungenstock, F., Wolters, S. & Freund, H., 2015, *Klastische Lagen in eingeschalteten Torfen im niedersächsischen Küstenholozän  Anzeiger für synsedentäre oder postsedentäre Einzelereignisse*. Siedlungs- und Küstenforschung im südlichen Nordseegebiet 38, 257-269.

Poster

## Holocene sea level rise and prograding coastlines in NW Germany: A beach ridge chronology based on shifting settlement remnants over time?

**Friederike Bungenstock**, **Annette Siegmüller**, **Saryn Schlotfeldt**

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The coastal systems of Northwest Germany are characterised by a general sea level rise since the beginning of the Holocene resulting in a general landward shift of the shoreline and coastal erosion.

The coastal area focused on in the poster is the northern part of Butjadingen situated very exposed between Jade Bay and Weser Estuary. It is a typical Holocene beach ridge system which is characteristically linked to stagnating or falling sea level which again is in contrast to the known sea level curve for the selected coastal section.

Within the marshland area, beach ridges represent higher and drier parts of the landscape, being in the focus for human settlement strategies. Consequently, in the presented study area the beach ridges are marked by rows of dwelling mounds which can be related to different time slides from the Roman Iron Age to the high-medieval period giving a chronology of the settlement history closely linked to the landscape history.

We aim to analyse the beach ridge systems in terms of age and progradation rates together with the development of the settlement cluster with the help of geological and archeological data jointly evaluated. To link the beach ridge system to the local sea level curve, local factors as paleogeography, sediment budget and single events have to be elaborated to understand seeming contradictions of sea level development and diachronous coastline displacement. The continous sedimentation at the slopes of the dwelling mounds and the differentiation of the settlement layers will give us a connection between the sedimentation and the reaction of the inhabitants which can be dated with archaeological methods.

We will present actual sea level data of the region and first maps of the beach ridge system and the dwelling mound rows.

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Bungenstock, F. & Weerts, H., 2010: *The high-resolution Holocene sea-level curve for Northwest Germany: global signals, local effects or data-artefacts?* International Journal of Earth Sciences (Geologische Rundschau) 99: *1687-1706.*

Siegmüller, A. & Mückeberger, K*., 2017: Structure and Function of Landing Places and Riverside Markets along the Lower Weser in the Roman iron Age.* Neue Studien zur Sachsenforschung 6: 273-283.

**Poster**

## The AD 1755 tsunami and other extreme wave events in Boca do Río, Portugal

**Lisa Feist[1], Piero Bellanova[1], Margret Mathes-Schmidt[1], Klaus Reicherter[1], Hannes Laermanns[2], Helmut Brückner[2]**

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The Portuguese coastline is exposed to extreme wave events, such as storms and tsunamis. In AD 1755 a strong earthquake followed by a tsunami destroyed large coastal areas including the city of Lisbon. In the sedimentary archive of the Boca do Río valley, at the western Algarve, the geological footprint of this tsunami is very well traceable and has been analysed by several authors.

In a new research project, the vulnerability of the coastal areas of the south-western Iberian Peninsula to extreme wave events is studied in connection with a decline of the Roman *garum* fish sauce production along the south Hispanic Atlantic coast in the 3rd century AD. In particular, the floodplain of the Boca do Río valley, Western Algarve, provides an excellent paleoenvironmental archive to investigate different causes for the decline (besides extreme wave events, e.g. climate deterioration), since *garum* production sites are located close to the recent shoreline and deposits of the AD 1755 tsunami are preserved in the sedimentary record.

Sediment cores from a transect approximately 350 m inland and parallel to the coast were taken during a field campaign in 2017 and later analysed in the laboratories of the RWTH Aachen University using a multiproxy approach. Visual sediment core descriptions, magnetic susceptibility, XRF, grain size and micropaleontological analyses enabled the identification of the AD 1755 tsunami deposit between fine-grained low-energy floodplain deposits at all coring sites. This event layer presents variegated tsunami characteristics, such as rip-up clasts, erosive basal contacts, fining-upward sequences and mud caps. Besides the AD 1755 tsunami deposit, another sediment layer was identified at one coring site which might have been associated with an extreme wave event. The XRF and magnetic susceptibility analyses revealed its clear marine origin, sandwiched in a terrestrial environment. This is supported by the micropaleontological analysis. According to grain size statistics this event layer seems to have been deposited during a storm. To date, no age estimates are available; therefore it cannot (yet) be associated with the 3rd century decline in the *garum* production. Furthermore, a predecessor event, comparable to the AD 1755 Lisbon tsunamigenic earthquake, has not been found to date.

**Poster**

## Organic-geochemical investigation of far-field tsunami deposits of Hawai'i

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Although being the remotest archipelago on Earth, the Hawai'ian Islands are threatened by both far-field tsunamis from around the Pacific and less frequent local tsunamis events. Historic tsunami events, like the 1946 Aleutian, 1952 Kamchatka, 1957 Aleutians and the 1960 Chile tsunami, have occurred on the Hawai'ian Islands, however, very little is known about prehistoric events.

This study focuses on the northeast shore of the island of O'ahu, which was affected by several tsunamis in the 20th century, using anthropogenic markers to characterize the geochemical fingerprint of tsunami deposits in the sedimentary record. The coastal marsh in the Kahana State Park, O'ahu, Hawai'i, was chosen as a sample location for a multi-proxy geochemical investigation of potential tsunami deposits. Using samples of pre-tsunami sediments, tsunami horizons, and post-tsunami deposits. The tsunami horizon is split into two samples, an upper part identified as a potential tsunami deposit and a lower part at the base of the deposit, into which organic geochemical compounds may migrate due to seeping.

The organic geochemical compounds were extracted from the samples using a solid-liquid extraction and analyzed by using gas chromatography-mass spectrometry (GC-MS). The pre-, post- and tsunami deposits were compared to each other related to anthropogenic markers concentrations. A total of 21 anthropogenic marker compounds such as polycyclic aromatic hydrocarbons (PAHs) and pesticides were identified of which 11 compounds were selected to study the event characteristics in the deposits in a detailed analysis. The anthropogenic markers are used to observe the maximal inundation, characterization, differentiation of pre-, post- and tsunami deposits and the determination of their source.

The results of the analysis show significant changes in concentration between the tsunami deposits and the underlying and overlying deposits, leading to the identification of the event layer within the cores. However, the limitations of the method are caused by the overall low concentrations of anthropogenic markers and pollutants due to the lack of industrial input sources and no anthropogenic environmental impacts in the Kahana Valley.

This study's geochemical characterization of tsunami deposits shows the need of further development, but the high potential of anthropogenic markers as an extension of investigative geochemical methods for high-resolution multi-proxy analyses of tsunami events in the sedimentary record.

**Keywords:** tsunami, Hawai'i, organic geochemistry, far-field tsunamis, anthropogenic markers, field study, tsunami deposit, Kahana Valley

**Poster**

## Geophysical investigations on the Eifel Aqueduct

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This research follows the hypothesis that archaeological remains can be used to quantify neotectonic movements. Around 80 AD, the Eifel Aqueduct was built to fullfill the increasing freshwater needs of the roman province capital *Colonia Claudia Ara Agrippinensium*, today known as the city of Cologne. Therefore, a 95.4 kilometres long aqueduct was built to get water from the Eifel with the use of natural slope inclination. The romans used wells in the Sötenicher limestone trough, which is a karst aquifer. Calacareous water was the favourite to roman taste, of which 20 000 m³ per day were streamed for about 190 years.In size, the aqueduct measures 0.7 metres in width, about one metre in height and was made out of concrete and stones. To preserve the water from frost, the aqueduct was buried beneath the ground. In medieval ages, people used the aqueduct remains for construction work. Thus, major parts were removed and the aqueduct route is nowadays just visible as a trench or not at all. Partly there are preserved archaeological remains in the original condition.

The aqueduct was built in a region that is exposed to extensional tectonic processes since the Lower Rhine Embayment initially opened in the Oligocene. Faults striking SE-NW are typical elements, which divide the region into fault blocks. Important fault blocks are the Erft, Ville and Cologne fault blocks. Recent earthquakes (Verviers 1692, Düren 1756, Euskirchen 1951, Roermond 1992, Alsdorf 2002) along faults indicate still ongoing tectonical processes, so called neotectonics. It can be assumed that the aqueduct was exposed to neotectonics in quaternary times. Therefore, studying the height and inclination of the archaeological remains could provide information about the amount of possible displacements. In a first approach, we will try to get high resolution ground images of the Eifel Aqueduct by using applied geophysical methods. Ground penetrating radar is widely used in archaeology because electromagnetic methods operate non-invasive. Especially in protected areas to get ground informations without excarvation, geophysical methods are beneficial. To detect the aqueduct, concrete and stones in contrast to surrounding soil will be visible by their different electromagnetic characteristics. Also during the building process, sediments were delocated and miss on natural features such as layering which is possible to detect.

First results of the ground penetrating radar measurements are promising for upcoming measurements. Therefore, the study area will be expanded to areas, where the aqueduct route is not yet verified.

**Poster**

## Extended periods of sea-level stability during mid-Holocene flooding of the Sunda Shelf

**Thomas Mann[1], Paul Simon Kench[2], Dominik Kneer[3], Eddie Beetham[2], Tilo Schöne[4], Alessio Rovere[1,5], Muh Aris Marfai[6], Hildegard Westphal[1,7]**

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Well-constrained data on the timing and magnitude of mid- to late-Holocene relative sea-level (RSL) fluctuations are required to further improve our understanding of modern and also future RSL changes on local and regional scales. However, published high-precise datasets from the Sunda Shelf in central Indonesia, an area that is considered particularly sensitive to future sea-level rise, are rare. This study presents results from a detailed microatoll-survey along the northern coastline of Central Java, Indonesia. The study site is characterized by the presence of numerous massive fossil microatolls, many of which indicate changes in former RSL positions due to their variable elevations above the height of living coral. Radiometrically calibrated ages and precise elevation information for the individual fossil microatolls indicate a rapid rise of RSL between 7.1-6.4 ka BP, culminating in a highstand of 1.85±0.22 m above today's mean sea level at about 6.7 ka BP. The morphological appearances of fossil microatolls furthermore reveal that RSL has been rising in progressive stages with centennial-scale periods of RSL stability.

Poster

## Postglacial slip rate variability of the Lastros normal fault (eastern Crete, Greece)

**Silke Mechernich**[1], **Hannah Dahms**[1], **Ioannis Papanikolaou**[2], **Klaus Reicherter**[3]

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Active extension in the Hellenic forearc results in a complex pattern of normal faults like the Ierapetra fault zone in eastern Crete. During the last 12 years, more than 20 shallow earthquake of magnitude 3-4 could be attributed to the Ierapetra fault zone, but no surface rupturing events have been reported in historical times. To date, two studies determined its faulting rates. First, uplifted marine terraces that are displaced by the transtensional Ierapetra fault indicate a throw rate of ~0.1 mm/yr during the past ~400 kyr (Gaki-Papanastassiou et al., 2009, Geomorphology). Secondly, geomorphic estimations along the Lastros fault suggest slip rates of 0.69 ± 0.15 mm/yr (Mason et al., 2016 Tectonophysics). This rate is based on the hypothesis that the exposed fault scarp was generated during postglacial times (15 ± 3 kyr). So far, no dating was obtained on offset features of the 11-km-long Lastros fault and the amount and frequency of past coseismic offsets is unknown.

We mapped indicators of the relative exposure duration along the bedrock fault plane at sites that most likely have only been exhumed by earthquakes and that were not affected by attached cemented colluvium on the fault plane. As exposure duration criteria of the fault plane we mapped colour contrast, lichen colonization changes, biocarstic fault plane roughness and solution flute terminations (method described in Mechernich et al., 2018, JGR). The data suggests coseismic offsets between 15-35 cm for the last three earthquakes, corresponding to earthquake magnitudes of $M_s$~6.2-6.5.

For absolute age constraints, cosmogenic $^{36}$Cl samples were taken at the best-preserved site with 11.8 m throw of the hillslope. Preliminary modelling of the $^{36}$Cl concentrations suggest temporal slip rate variabilities with 0.2-0.7 mm/yr during the last 2.9 ± 1.8 kyr (last 3 earthquakes), preceded by a rate of 0.6-1.2 mm/yr from ~2.9-10 kyr. The apparent exhumation rate of the upper part (0.2-0.3 mm/yr, last ~10-36 kyr) is probably highly influenced by non-tectonic processes.

Poster

## Foraminifera as markers of Holocene sea-level fluctuations and water depths of ancient harbours — A case study from the Bay of Elaia (W Turkey)

**Martin Seeliger**

*University of Cologne, Germany*

The absence of common sea-level indicators in the study area of Elaia, Pergamum's harbour city in Hellenistic and Roman times, forced to establish a new reliable indicator, which was found in the foraminifera associations inconnection with the transgressive contact. The strength of this indicator is the exclusion of post-depositional compaction. Accompanied by a well-dated archaeological index point at a breakwater, the micropalaeontological indicator enabled the establishment of a reliable regional sea-level curve (RSL curve) for the Bay of Elaia. It is in good agreement with other curves for the Aegean region and in general agreement to the glacio-hydro-isostatic model for the region. Our sea-level curve proves, for the first time at a continental site on the Turkish Aegean coast, the today's sea-level peak. Water-depth modelling for the so-called closed harbour of Elaia reveals the capacity to fully accommodate the common ship classes of Hellenistic and early Roman times until around 150 CE, while water depth estimates for the so-called open harbour of the city verifies the usage of the adjacent ship sheds during Elaia's prime.

Poster

## Towards using sedimentary evidence of modern tropical cyclone deposits for long-term hazard assessment in Chaung Thar, Myanmar

**Katharina Seeger**

*University of Cologne, Germany*

Tropical coastal areas are prone to extreme wave events (EWEs) like tropical cyclones (TCs) and tsunamis. Along with monsoonal precipitation and riverine floodings, tropical storms are a compound of hazards whose consequences cannot be completely estimated yet as TC activity is related to climatic changes in El Niño-Southern Oscillation (ENSO) and monsoon circulation.

Though the Bay of Bengal was affected by severe floodings in the past (e. g., the Indian Ocean tsunami 2004, TC Mala 2006, and TC Nargis 2008), there is little known about their impact on the western coast of Myanmar. Besides the Bay of Bengal earthquake triggered at the Rakhine segment in AD 1762, which is associated with a tsunami, long-term history of EWEs has not been taken into account so far. This is, however, indispensable for assessing their magnitude and frequency and finally to establish a hazard assessment system.

Analysing sedimentary archives by combined analyses of granulometry, geochemistry and optically stimulated luminescence (OSL) could serve as a valuable approach to characterise past events on a local scale and thus might extend the historical record.

At Chaung Thar, situated at the Rakhine coast, there is evidence for two allochthonous sand sheets deposited by TCs that made landfall in this area. The uppermost sand layer is known to be deposited by TC Mala 2006 and serves as a modern analogue for the historic event. Both layers reflect typical sedimentological characteristics of EWEs and originate from the same sources out of the foreshore while their internal structure is slightly different.

Luminescence dating of quartz grains out of the TC Mala deposit reveals satisfying results with remnant ages of less than ten years, if the minimum age model is used, and allows for inferences about bleaching characteristics. The historic event dates to AD 1929–1953 by applying OSL. However, the preservation potential of these sediments is very low as carbonate weathering and soil formation already started to overprint them, whereby swale areas and local depressions at the back side of the beach barrier turn out as the most promising archives. Due to the limit of preservation and together with the lack of knowledge of further former events, the sedimentary evidence of TC deposits at Chaung Thar may thus not be useful towards a local long-term hazard assessment but show the potential of the applied methods for such evaluations.

Talk

## Sedimentary and erosional evidence of hurricane Irma on the British Virgin Islands

**Michaela Spiske[1], Jessica Pilarczyk[2], Stephen Mitchell[2], Robert Halley[3]**

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Severe storms are a major threat to coastal areas and communities. The 2017 Atlantic Hurricane Season drew renewed attention to the worldwide need for storm risk assessment as it was the costliest season on record, with damages associated with hurricane *Irma* exceeding 200 billion US$. *Irma* was the strongest recorded hurricane to form in the Atlantic Ocean. It reached the northwestern Caribbean Islands as a category 5 hurricane on Sept. 5$^{th}$ 2017.

A post-hurricane survey was conducted on Anegada (British Virgin Islands). The project takes advantage of pre-event field data collected on Anegada in earlier years that allows for a detailed comparison of pre- and post-*Irma* data. *Irma* passed ca. 35 km south of Anegada. Maximum wind speed on Anegada was ~256 km/h, the peak wave period was ~32 s and related maximum offshore wave heights were ~17 m. *Irma* had a surprisingly weak storm surge of <3 m as indicated by wrack lines and an overwash deposit. The small surge may be explained by the fact that *Irma*'s eyewall passed south of the island and winds were mainly shore parallel. Thus, even though a category 5 hurricane, very close to the island, *Irma* does not represent the worst-case scenario for a storm event on Anegada.

Substantial coastal erosion occurred on Anegada's north shore. A steep erosional scarp of about 1 to 1.5 m height and a retreat of the coastline by several meters were documented. While erosion dominates the northwest and central north shore, depositional evidence is present along the northeastern and southern shore. Thick sand sheets that cover beach sand have a max. thickness of ca. 35 cm. Deposits are massive and well-sorted carbonate sands. Small washover lobes that contain shell hash have sediment thicknesses of 5 cm. A pre-existing coast-parallel coral rubble ridge was entirely reworked. Cobbles and boulders were moved several meters in landward direction. Few cobbles were washed into the sea, moved shore parallel towards the west and transported back onto the coastal platform.

Talk

## Neotectonics along the Bogd Fault Zone, SW Mongolia - Effects on the evolution of the Orog Nuur (Lake) Basin?

**Jorien Leonorah Ninon van der Wal[1], Veit Christian Nottebaum[2], Klaus Reicherter[1], Georg Stauch[2], Christopher Weismüller[1], Frank Lehmkuhl[2]**

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Characterized by the occurrence of high magnitude earthquakes and arid climate conditions, the Gobi Altay ranges of SW Mongolia offer an interesting location for paleoseismological investigations. The NW-SE to E-W striking Gobi Altay result from active intraplate tectonics overprinting and reactivating older crustal fabrics; at its northernmost margin this is expressed by sinistral transpression along the Bogd Fault Zone (BFZ). As a result of the 1957 M8.3 earthquake, the BFZ ruptured over a length of >250 km and up to 7 m horizontal- and 6 m vertical offsets were measured. Slip rates along both strike-slip and thrust- dominated fault segments are slow: 0.5-1 mm/yr and 0.1 mm/yr, respectively. To the north, the BFZ is bordered by the Orog Nuur (Lake) Basin that is part of the SW-Mongolian Valley of the Lakes which has been subject to Quaternary aridification.

In this study we use high resolution digital elevation models (DEMs) retrieved from drone images and ground-penetrating radar (GPR) measurements across active faults to reconstruct earthquake activity along the BFZ. We combine these geological and geomorphological observations with OSL (Optically-Stimulated Luminescence) and cosmogenic nuclide dating to evaluate the effect of active faulting on sediment fluxes into and within the Orog Nuur Basin. Ultimately, we aim to understand the interplay between active tectonics and climate variabilities and their effects on the aridification of Orog Nuur.

Field observations include little degradation of fault scarps, beach deposits at multiple elevations and liquefied lake sediments. Morphotectonic features such as offset, blocked and beheaded fluvial markers and variabilities in fluvial deposits across surface ruptures are ample and suggest that drainages have been affected by a multitude of earthquakes. Subsurface structural and sedimentological observations from

GPR measurements (up to 22 m depth) are not only used to characterize past earthquakes in terms of magnitude, slip rates and return intervals, but will also need to be correlated in detail with high resolution drone DEMs to create an understanding of the surface processes at play.

Talk

## Holocene sea level and landscape reconstruction of the East Frisian Penninsula/Southern North Sea - a base to investigate coastal archives

**Friederike Bungenstock, Martina Karle**

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The response of coasts to global sea-level rise is highly variable even on a regional scale. Knowledge of driving coastal processes alongside the regional sea-level history is therefore indispensable when the response to global sea-level rise is to be assessed.

Sea level data for the tidal basin of the East Frisian Island Langeoog have been collected and evaluated by profile sections and seismic tracks in order to create a Holocene sea level curve representative for this area. Combined with an existing model of the base of Holocene deposits (NIBIS map server, official portal to the Geodata of the Lower Saxony Soil Information System NIBIS), assumptions of paleo tidal ranges and the lithostratigraphical data of more than 5000 cores, archived at the LBEG (Geological Survey of Lower Saxony), palaeogeographical maps from 9000 BP onwards could be reconstructed. Although there is a lack of absolute chronology, these maps deliver a general picture of the depositional history and change of lithological units over time.

Due to the lack of datings and further landscape information mainly on vegetation history and ecological parameters these maps initiated the WASA (Wadden Sea Archive) project. The interdisciplinary research project integrates sedimentology, hydroacoustics, geochemistry, palaeoecology and archaeology in a multiproxy approach involving exploration, analysis and predictive modelling. The focus of the project is to identify and investigate coastal archives in order to reconstruct the development of the Quaternary palaeo-landscapes and to model the environmental conditions for site location preferences of former human societies.

Bungenstock, F. & Weerts, H., 2010: The high-resolution Holocene sea-level curve for Northwest Germany: global signals, local effects or data-artefacts? *International Journal of Earth Sciences (Geologische Rundschau)* **99**:1687-1706.

Goldhammer, J., Karle, M. (2015): Geoarchaeological research in the Wadden Sea area of Lower Saxony. *Siedlungs- und Küstenforschung im südlichen Nordseegebiet*, **38**: 59-70.

Talk

## Increasing the accuracy of beach rocks as sea level indicators by sedimentological facies analysis

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The reconstruction of past relative sea level variations is essential as it allows predictions about upcomming developments. Hereby, the establishment of sea level index points is crucial. While beach rocks are a sure marker of paleo coastlines, their use in the establishment of sea level index points has been criticised due to often meter-scale insecurities regarding the vertical range of their formation. Sedimentological facies analysis poses a solution to this problem. Overall goal of our research is to study the variety of beach rock lithofacies and their use in sea level reconstructions. To achieve that, a number of key areas worldwide needs to be investigated. The beginning made the NE coastline of Oman.

The NE coast of Oman, is dominated by Palaeocene to early Eocene limestone. These formations do not only form the coastal bedrock but also the 1500 m high Selma Plateau. The limestones are heavily karstified. A set of 12 staircased, wave-cut, marine terraces is observed parallel to the coastline. While the upper terraces are completely abraded and beach rocks are the only remaining sedimentary cover, the lower terraces are depositional and beach rocks occur alongside with alluvial, fluvial, and shallow marine facies. The terrace levels are allocated to Marine Isotopic Stages MIS 5e to MIS 15, based on dating via cosmogenic nuclei.

Eight beach rock outcrops were localised by geological mapping. Sedimentological logs of all outcrops as well as thin sections of all suitable layers constitute the basis of the facies analysis. The observed layers were grouped together in lithofacies based on their sedimentological properties. Finally, each outcrop was interpreted regarding its depositional realm taking the stratigraphic relations of different lithofacies into account. Eight lithofacies were identified and grouped together in six facies associations, which are:

1. Lower Backshore on sandy or gravelly beaches
2. Swash dominated Upper Foreshore
3. Surf dominated Lower Foreshore
4. Breaker dominated Plunge Step
5. Low energy Estuarine Margin
6. Upper Shoreface on sandy or gravelly beaches

From a large uncertainty of several meters, these exposures are now allocated to a certain position relative to paleo sea level which results in a lowered uncertainty on a decimeter scale.

Talk

## *Ex-situ* quantification of sea-level index points and its use in the reassessment of the last interglacial sea-level database

**Thomas Lorscheid**[1,2], **Alessio Rovere**[1,2]

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Precise predictions of future sea-level rise are essential for developing models of future climate change and shoreline protection strategies. These predictions are calibrated to the sea-level highstand in past warmer climates and need consequently accurate estimates of the paleo sea levels. Besides the Holocene, the most studied past period in sea level studies is the last major interglacial, the Marine Isotopic Stage (MIS) 5e between ca. 128 and 116 ka, when global sea level was ca. 6-9 m higher than today. The only direct observations of sea level in this time, can be made by the investigation of paleo relative sea-level (RSL) indicators. As RSL indicators, any geological feature can be used, that has a quantifiable relation to the sea level during the time of its formation. This relationship is called the indicative meaning, combining the vertical distance between the feature and sea level (i.e. the reference water level) and the possible height variability (i.e. the indicative range). Although a large number of studies have assessed the paleo sea-level elevation, one of the fundamental problems with most of these studies is the lack of using the description of the indicative meaning, as it is done for Holocene sea-level studies, as standard tool to add an uncertainty to the RSL indicator.

The vast majority of reported RSL indicators can be described by using 10 geomorphological categories. For each category, the upper and lower limit of the RSL indicator, which describe the indicative meaning, can be defined by using relevant wave- and tide-related datums. Although the general categorization of RSL indicators helps in describing the indicative meaning in a standardized way, the corresponding limits are often hard to quantify on specific study sites. In the best case, this quantification should be done using a nearby modern analog of the landform and described alongside with the study and elevation measurement of the RSL indicators.

If an in-situ determination of the indicative meaning is not possible, different morpho- and hydrodynamic equations and global wave and tide datasets can help in quantifying these limits according to the categorization of RSL indicators. In this presentation, we will show which datasets and relations can be used in order to calculate the indicative meaning on a remote and global scale. Using these simple equations is a valid method to establish the indicative meaning for regional or global datasets or if no site-specific data is available.

Talk

## Orbital forcing of the hydrological cycle and sea-level during greenhouse climate: The importance of aquifer-eustasy

**Jens Erik Wendler**, **Ines Wendler**

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The hydrological cycle is a central representation of Earth's pulsating climate system. Water cycling is forced by orbital cycles which create major fluctuations in water exchange between Earth's two main water reservoirs, the oceans and continents. Particularly on periods of 400-1000x$10^3$ years this cycling is responsible for global eustatic fluctuations in sea-level with amplitudes on the order of 50 m. The major climate states of Earth are icehouse, greenhouse and hothouse epochs at durations of tens of millions of years. We summarize the conceptual models for hydrological cycling responsible for sea-level fluctuation during these three climate states. While under icehouse climate conditions sea-level changes are caused by glacio-eustatic forcing, the driver of eustatic sea-level fluctuations under greenhouse conditions, lacking polar ice shields, is aquifer-eustasy. As an example for a greenhouse climate, we review evidences that link proxies for climate and sea-level for the mid-Cretaceous sea-level history. Based on sequence stratigraphy, astrochronology and mineralogy the aquifer-eustatic process, that is the cyclic exchange of water between the oceans and the dynamic continental water storage (aquifers), can be detected. We show that both aquifer-eustasy and glacio-eustasy formed a combined sea-level response throughout Earth history, with dominance of aquifer-eustasy during the greenhouse climate mode. During the icehouse mode, aquifer-eustasy apparently remains active as a background process, but is outpaced by the glacio-eustatic effect.

# 6b) Impact cratering throughout the solar system

Talk

## Plaeostress and final strain estimation in experimental impact crater: clues to shock wave behavior

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The behavior of the shock wave, while it passes through the target, has been the focus of many studies. The shock wave provokes complex brittle, ductile, elastic and plastic deformation [1–3]. The deformation imparted by them give clues to the behavior of the shock waves such as its propagation direction, tensile or compressive phases, resultant pressure, and temperature, etc. [4,5]. The geometry of the shock wave is also a focus of many investigations; however, it is complex because of the wave reflection, refraction, and superposition. The present study applies the classical techniques of finite strain analysis and the paleostress analysis of biotite kink bands[6] to determine the final resultant strain and principal stress directions. The resultant strain provides a quantification of the final deformation imparted due to all the phases of the shock wave and their superposition. σ1 in the target provides the geometry of the shock wave front.

References

1. Kenkmann, T., Poelchau, M. H. & Wulf, G. Structural geology of impact craters. *J. Struct. Geol.* **62,** 156–182 (2014).

2. Agarwal, A., Reznik, B., Alva-Valdivia, L. M. & Srivastava, D. C. Alternating augite-plagioclase wedges in basement dolerites of Lockne impact structure, Sweden: A new shock wave-induced deformation feature. *Meteorit. Planet. Sci.* **52,** 458–470 (2016).

3. Agarwal, A., Reznik, B., Kontny, A., Heissler, S. & Schilling, F. Lingunite-a high-pressure plagioclase polymorph at mineral interfaces in doleritic rock of the Lockne impact structure (Sweden). *Sci. Rep.* **6,** 25991 (2016).

4. Agarwal, A., Reznik, B. & Kontny, A. Formation of nanoscopic Lingunite and alternating augite- plagioclase wedges at Lockne impact crater, Sweden. in *European Planetary Science Congress* **12,** (2018).

5. Agarwal, A., Kontny, A., Srivastava, D. C. & Greiling, R. O. Shock pressure estimates in target basalts of a pristine crater: A case study in the Lonar crater, India. *Geol. Soc. Am. Bull.* **128,** B31172.1 (2016).

6. Srivastava, D. C., Lisle, R. J., Imran, M. & Kandpal, R. A New Approach for Paleostress Analysis from Kink Bands: Application of Fault-Slip Methods. *J. Geol.* **107,** 165–176 (1999).

Talk

## Shower of extraterrestrial material onto the Earth-Moon system

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Earth and the Moon were, for the last 3 billion years, exposed to a somehow continuous bombardment of extraterrestrial material. The global lunar impact record is well preserved, but sample availability severely limits our knowledge regarding variations in the impact flux over time [1,2]. In contrast the terrestrial crater record is well accessible but highly fragmented. Nevertheless, several episodes of intense bombardment are recognized. The most prominent episodes are the late Eocene shower of extraterrestrial material [3,4], and the mid-Ordovician shower of L chondritic meteorites [5]. Other episodes of an increased delivery of extraterrestrial material to Earth include an increased dust delivery during the late Miocene, and the cretaceous K1 and K3 events [6]. A variety of astronomical processes leading to a shower of cometary or asteroidal fragments to Earth were proposed, reflecting our understanding of Solar System workings and the collisional history of planetary bodies [7-10]. Detailed studies of time intervals with an apparently elevated flux of extraterrestrial material to Earth will further improve our understanding of the processes in space instrumental for the bombardment of the terrestrial planets. Trying to correlate and combine the well preserved but poorly accessible lunar impact record with the fragmented but accessible sedimentary and impact record on Earth could substantially improve our knowledge regarding the flux of extraterrestrial material onto the Earth-Moon system.

References: [1] Baldwin, R. B., 1971. Icarus 14, 36-52. [2] Neukum, G., Ivanov, B., and Hartmann, W.K., 2001. Space Science Reviews 96, 55-86. [3] Farley, K.A., 2009. Geological Society of America Special Papers 452, 27-35. [4] Fritz, J., Tagle, R., and Artemieva, N., 2007. Icarus 189, 591-594. [5] Schmitz, B., Tassinari, M., and Peucker-Ehrenbrink, B., 2001.Earth and Planetary Science Letters 194, 1-15. [6] Farley, K.A., Montanari, A., and Coccioni, R., 2012. Geochimica et Cosmochimica Acta 84, 314-328. [7] Hut, P., Alvarez, W., Elder, W. P., Hansen, T., Kauffman, E. G., Keller, G., Shoemaker, E. M., and Weissman, P. R., 1987. Nature 329, 118 - 126. [8] Zappala, V., Cellino, A., Gladman, B. J., Manley, S., and Migliorini, F., 1998. Icarus 134, 176-179. [9] Fritz, J., 2012. Icarus 221, 1183-1186. [10] Wooden, D. H., Cook, A. M., Colaprete, A., Glenar, D. A., Stubbs, T. J., and Shirley, M., 2016. Nature Geoscience DOI: 10.1038/NGEO2779.

Talk

## Shock pressure experiments on single silicate minerals

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**Introduction**

A recent discussion [1] is developing about the suitability of shock classification currently being used to grade meteoritic material that has experienced shock from impact cratering. We present initial work that begins to expand on this discussion by recreating high shock pressure in hypervelocity impacts in a laboratory environment between 6 and 182 GPa and observing how silicate minerals are altered chemically and structurally. This work follows on from [2] which investigated the observed Raman shift in shock olivine powder.

**Method**

We have shocked powdered and whole grains of diopside, enstatite and peridot, using a light gas gun facility at the University of Kent [3] between 1 and 8 $kms^{-1}$. The silicate material was fired into Al foil and the resulting residues of material located in the craters were analysed using Raman (532 nm), SEM and FEGSEM.

**Initial results**

These initial results indicate that a significant change in the composition of the mineral can occur when experiencing different shock pressure depending on the structure of the mineral.

The Enstatite ($En_{86}Fs_{13}Wo_{1}$) residues show very few peaks when analysed by Raman and many are lost in the background. This is observed at all the shock pressures investigated which suggest that shock affects the Raman signal of Enstatite at a much lower shock pressure then olivine, at about 29 GPa.

The diopside mineral investigated had a composition of $Wo_{49}En_{48}Fs_{3}$ from Jaipur, India supplied by M. McCanta, University of Tennessee [4]. The wavenumbers do vary compared with the unshot spectra but no correlation is observed between size/direction of shift and the shock pressures, this suggests that there are no observed effects up to a shock pressure of 145 GPa after which the peaks are not observed.

The peridot experiments ($Fo_{96}$) found a pressure of 108 GPa is required before large olivine mineral grains significant structural changes.

This work is ongoing and will soon include other common minerals, by understanding how each mineral reacts at different shock pressures the experiments can move on to shock syntheses of whole rock facies to understand the shock interaction between the different minerals at grain boundaries and other mineral interfaces.

**[1]** Stöffler, D., *et al MAPS*, 53(1), pp.5-49. (2018)

**[2]** Harriss, K H., and M. J. Burchell, *MAPS* 51, no. 7 (2016): 1289-1300.

**[3]** Burchell, M J., *et al*, MST, 10, 1 (1999): 41.

**[4]** McCanta, M. C., and M. D. Dyar. *MAPS,* 52, no. 2 (2017): 320-332.

Poster

## Quantification of the fractal dimension of cataclasites in granitoid target rocks of the Chicxulub impact crater (Yucatán peninsula, Mexico) using SAGA GIS image analysis

**Sabine Kölln**, **Olaf Conrad, Ulrich Riller**

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The 66 Ma Chicxulub impact crater ranks among the best-preserved, large impact craters with a peak ring on Earth. Off the coast of Yucatán, the peak ring of the crater, measuring about 80 km in diameter, is buried under approximately 500 meters of post-impact sedimentary rocks. IODP-ICDP Expedition 364 drilled the peak ring in 2016 in order to unravel the deformation mechanisms responsible for peak-ring formation. An about 800 meters long section of variably fractured granitoid target rocks, hosting plenty of cm- to dm-thick proto-, meso- and ultracataclasite, was recovered.

Terrestrial impact craters the size of Chicxulub form within less than ten minutes through collapse of a transient cavity, 100 km in diameter and 30 km depth. Cratering, thus, requires target rock to temporary weaken by a loss in frictional strength and cohesion. Currently, three hypotheses are discussed as possible causes for such weakening: acoustic fluidization, thermal softening and strain rate weakening. Investigating the fractal dimension (D-value), i.e., size-frequency distribution of fragments in cataclasite promises to shed light on the weakening mechanism. More specifically, the variation of fractal dimensions is expected to clarify to what extent cataclasite zones formed by a single process. Moreover, comparison with experimentally determined D-values may hold information on the magnitude of shearing-induced deformation during cataclastic flow, i.e., peak-ring formation. In this regard, fragment ellipticity might be of importance as well.

We demonstrate the work flow and results of quantifying the fractal dimension using the open-source Geographic Information System (GIS) software SAGA (System for Automated Geoscientific Analyses). The analyses are based on thin sections and application of a semi-automatic image segmentation workflow, in turn built on an automated seeded region growing algorithm. Polygonization of the grain fabric entails spectral information of individual mineral phases. This allows us to obtain quantitative information on the different types of cataclasites regarding their amount of matrix and their fragment geometry.

**Poster**

## The possible influence of the cosmic Impact of Rochechouart (France) on the NE Paris Basin

**Natascha Kuhlmann[1], Jean Thein[1], Thorsten Nagel[2], Sven-Oliver Franz[1], Dieter Garbe-Schönberg[3]**

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About 201 million years ago the large asteroid of Rochechouart (diameter ~1,5km) hit the Variscan crystalline basement of the NW Massif Central in France near Limoges. It left a crater of approximately 50 km in diameter [1], generating an earthquake of magnitude 11.4 [2]. The original morphology of the crater has largely been eroded. Until today various authors discuss the influence of the Rochechouart impact on the Triassic/Jurassic mass extinction. However, it is relatively clear that the Rochechouart impact is too small to create global influences in biosphere and geosphere. Nevertheless, the effects of this catastrophic event can be recognized by typical sediment features in the shallow marine area in the NE Paris Basin, and due to the smaller distance even better in the northern Aquitaine Basin. The record of sediments from the upper Nor until the lower Hettangium is well exposed and allows studying environmental effects of catastrophic events on a stratigraphic sequence. In several drillcores and outcrops in Luxemburg, Germany and France, exotic and chaotic sediment successions were recognized as seismites and tsunamits, which are interpreted as results of the Rochechouart impact. The seismites between the lower and upper Rhaetian are overlain by a deformed horizon with flame structures, pebble-horizons, vertebrate remains, which have been accumulated within the tsunami waves.

Similar horizons have been described from western United Kingdom and eastern Ireland [3] and are still under debate. In the first publications the authors interpret the Manicouagan impact to be a candidate to produce the tsunamites and seismites. However, the known radiometric age of the Manicouagan crater is too old (~214 Ma) and therefore had no influence on the NE Paris Basin. A highly diagnostic feature of large asteroid impacts on planet earth is among others the extreme concentration of platinum group elements (PGE) in fine grained ejecta, for example at the K/T boundary. No chocked grains (e.g. quartz with planar deformation features, microtektites or suevit glasses) have been found until now in the research area. Several PGE-nuggets and a rhodium-anomaly, both detected in the fine grained sediments of the tsunamite bed, could however well be interpreted as ablation droplets of the asteroid impactor, passing through the atmosphere.

[1] Lambert, P. (2010) Geol. Soc. Amer. Spec. Paper 465. [2] Schmieder, M., Buchner, E., Schwarz, H. W., Trieloff, M., Lambert, P. (2010) Meteor. & Planet. Sci. 45, 8, 1225–1242. [3] Simms, J. M. (2007) Palaeo3, 244, 407-423.

**Talk**

## GRADED SUEVITE IN THE IODP-ICDP EXPEDITION 364 CHICXULUB M0077 CORE: CLUES TO CRATER MODIFICATION AND MATERIAL TRANSPORT

**Jens O. Ormö[1], Sean P. S. Gulick[2], Michael T. Whalen[3], Kazuhisa Goto[4], David T. King. Jr.[5], Erik Sturkell[6], Joanna V. Morgan[7]**

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The cored sequence begins with ~110m of post-impact Paleogene hemipelagics and pelagics that are followed downwards by ~130m (617 to 747mbsf) of polymict suevite. This overlies impact melt rock and basement rocks (747 to 1334.73mbsf). We have estimated the effect of marine environment on deposition of the suevite. We apply the line-logging method previously used in studies of water-laid sediments at other marine impact craters. Instead of using actual drill core, in this instance our technique was applied to high-resolution core photos. In the suevite (core unit 2), 2376 clasts were analysed between depths 672.01mbsf and 715.93mbsf.

Below 706mbsf, clast size and sorting, and matrix/clast support varies strongly. Above 706mbsf, there is a general fining-up trend, and gradual increase in sorting from moderately to well sorted. At 697mbsf, there is a second noteworthy shift in several parameters, especially a break in an otherwise upwards increase in roundness to a level of high angularity that continues to the top of the logged section. The interval between 697mbsf and 706mbsf is also characterized by a near absence in the otherwise rather common brown carbonate (“upper target II”) clasts and green melt. Instead the interval is dominated by grey melt fragments, and the amount of tan carbonate (“upper target I”) and other target rocks remain essentially unchanged over the 697-706mbsf interval, followed by a relative decrease upwards.

The high amount of angular melt fragments above 697mbsf may indicate both fall-back of melt into the seawater surrounding the crater, as well as subsequent rip-up of melt fragments from rapidly quenched impact melt and avalanche breccias at the peak ring inside the crater. The high angularity suggest explosive disruption of melt in contact with the water, and insignificant abrasion during the strong, but short duration, aquatic transport. Field observations in the area of Belize-Guatemala-Mexico suggest that tan carbonates likely come from the upper part of the Yucatan Group, whereas brown carbonates likely come from the lower part.

We think that an initial stage of slumping from the newly formed peak ring is followed (at 706mbsf) by a forceful resurge flow that carries mainly grey melt fragments, and uppermost target material (e.g., tan carbonate) and some lower target material. The flow then shifts (at 697mbsf) to carry mostly green melt fragments and lower parts of the upper target (e.g., brown carbonates) as well as some lower target material. The resurge was followed by oscillating water movements.

**Talk**

## Preferred orientation of shock-induced microstructures in quartz and feldspar grains as marker for shock wave propagation direction

**Lidia Pittarello[1], Ludovic Ferrière[2], Gordon R. Osinski[3]**

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Shock effects in minerals are used as shock barometer after calibration based on single crystal shock recovery experiments. Although this provides a reliable pressure estimate in first approximation, in the case of polymineralic rocks, the interaction between shock waves and crystals of different internal symmetry and orientation might affect the recorded shock intensity, as suggested by the strongly heterogeneous distribution of shock effects in minerals within a given sample (i.e., as seen at the thin section scale). To address this problem, we have selected shatter cone samples, where the main shock wave propagation direction can be roughly constrained, formed in granitoids recording different pre-impact tectonic deformation stages, from undeformed to strongly foliated, from Charlevoix (Canada), Keurusselkä (Finland), and Manicouagan (Canada) impact structures. Thin sections were cut normal to shatter cone surface and striation. Planar microstructures, such as planar deformation features (PDFs) in quartz and planar fractures (PFs), PDFs, and (likely shock-induced) micro-twins in feldspar were measured with the Universal-stage and plotted using the program Stereo32, using as reference either the foliation (whenever present) or the long side of the thin section. For quartz containing PDFs, c-axis orientation was also plotted, to exclude any bias caused by pre-impact dynamic recrystallization.

Preliminary results show that planar microstructures in feldspar preferentially form along crystallographic directions that are sub-parallel to the shock wave propagation direction, assuming that the shatter cone striation represents the propagation direction of the scattered shocked waves in the selected sample. The same is also observed for PDFs in quartz; Quartz grains with c-axis lying on the plane sub-perpendicular to this “main direction” seem to be more favorably oriented to develop PDFs than those with c-axis sub-parallel to the shock wave propagation.

In conclusion, the crystallographic orientation of mineral grains with respect to the shock wave propagation does affect the intensity and the type of shock effects in minerals. Therefore, the preferred orientation of shock induced planar microstructures in minerals from a randomly collected sample may allow the identification of the shock wave propagation direction also where it cannot be inferred by other features (such as shatter cone striation), providing information on the impact cratering process at the field scale. Further work on oriented drilled core samples is in progress, to check the validity of the method.

**Talk**

## Shock deformation in Calcite: Results from Impact Cratering Experiments into Marble

**Michael Poelchau, Thomas Kenkmann, Rebecca Winkler**

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An impact cratering experiment with a Carrara marble target was conducted with a two-stage light gas gun at the Fraunhofer EMI in Freiburg, Germany. A 2.5 mm diameter Campo del Cielo iron meteorite impacted the target at ~5 km/s. After the experiment the target block was sawed in half and a thin section of the crater subsurface was systematically scanned with an electron microscope to map microstructures in detail. TEM foils were prepared from in situ crater floor material and from a depth of 300 µm below the crater floor.

With a diameter of 56.6 ± 4.2 mm the crater is unusually small. Microanalysis of the subsurface shows twin lamellae and open cleavage as the main deformation features with additional intra-granular cracks and tensile fractures. The uppermost crater subsurface shows heavily deformed calcite grains with brownish color in plane polarized light, and a lack of extinction and reduced birefringence in cross polarized light. These features are observed to a depth of ~1.5 projectile diameters. SEM and TEM microscopy show a predominance of micro-twins in three orientations in single grains. The average twin density, measured in TEM-foils at constant magnification, exceeds 1000 twins/mm and locally reaches values of 30000 twins/mm.

The peculiar optical behavior of shocked calcite is explained with the presence of extremely high micro-twin densities, partly high dislocation densities and the opening of twin-planes as cleavage planes. The spacing of twins is in the order of the wavelength of visible light, in some regions remarkably below the wavelength of light. The twin structure works as a diffraction grating. The lack of extinction under crossed polarized light is due to the dispersion in several directions, in particular if three twin orientations are present.

Tectonic studies reveal a systematic relationship between twin density in calcite and the applied shear stress. Comparison with numerical models suggests that calcite grains of the TEM foils experienced peak shear stresses between 800 and 1000 MPa. The relationship between micro-twin density and the estimated shear stress matches with calcite twin piezometers derived for tectonic deformation and suggests that calcite twin piezometry is applicable to the shock stage. Shock-microtwinning in calcite and the associated optical behavior of calcite could be applied as useful shock indicators to natural craters, and will be tested in the near future.

Talk

## Viscous relaxation of crust underlying large terrestrial impact craters: Evidence from the Sudbury Impact Structure, Canada, and analogue experiments

**Ulrich Riller**, **Stephani Teuber**

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Evidence of long-term modification of terrestrial craters caused by viscous relaxation of crust is rather sparse, but paramount for fully understanding large-meteorite impact processes. Owing to the excellent exposure, access and post-impact tilting of impact-generated lithologies and structures, Sudbury appears to be the only large, terrestrial impact structure that allows for a structural analysis aimed at unraveling long-term modification of large impact craters. Besides providing the first quantitative structural evidence for long-term crater modification on Earth, understanding this process at Sudbury is also important for designing exploration strategies of Cu-Ni and platinum group element (PGE)-rich ore deposits.

The following structures and mineral fabrics associated with the 1.85 Ga Sudbury Igneous Complex (SIC), the deformed relic of an impact melt sheet, are traditionally attributed to the Paleoproterozoic Penokean orogeny: (1) contact-parallel igneous mineral fabrics in the SIC; (2) contact-parallel, high-temperature metamorphic fabrics in the thermal aureole of the SIC and (3) granitoid dikes, known as Offset Dikes, emanating from the SIC and derived from (partially-melted) target rocks. These structures are genetically related to cooling and solidification of the SIC, which occurred within approximately ten thousand years after impact and, thus, substantially faster than the duration of Penokean deformation. Offset Dikes, in particular, have been interpreted as equivalents to lunar crater floor fractures. In fact, simple two-layer analogue models using viscous and granular materials for the lower and upper crust, respectively, scaled to length, time and viscosity display polygonal fractures in the model craters as a result of isostatic (i.e., viscous) re-equilibration of model crust. Moreover, PGE-rich Cu-Ni sulfides occupy tensional fractures in target rocks immediately underlying the SIC. The sulfides segregated from the silicate impact melt upon cooling of the melt below about 1450°C and accumulated at the base of the melt sheet, from which they migrated into dilational target rock fractures, akin to the emplacement of Offset Dikes.

In summary, the mentioned structures have been attributed erroneously to orogenic deformation and underestimated with regard to deformation caused by long-term crater modification. In fact, they all amount to vertical thinning and horizontal extension, i.e., oblate strains, of the SIC and underlying target rocks, which is consistent with crater floor modification caused by viscous relaxation of crust known also from remote sensing studies of the lunar surface and Mercury.

Talk

## No isotopic dating needed: Pinning down the Ries meteorite impact at Nördlingen, South Germany, at 14.870 ± 0.005 Ma by solely geological tools

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The Ries crater is among the most intensely studied meteorite impact structures worldwide. Knowledge of its exact age is important for stratigraphic reasons, because an impact-generated layer of ejected Jurassic limestones, the so-called Brockhorizont, forms the most prominent marker horizon within the Middle Miocene molasse sediments of the Northern Alpine Foreland Basin. With one exception (Rocholl et al, 2017; U-Pb dating of bracketing tuffs), age determinations of the Ries event is based on K-Ar, $^{40}Ar/^{39}Ar$ and fission track analyses of impact melts and tektites (moldavites). Analyses started in the early 1960s (Gentner et al., 1963) and continued until now (Schmieder et al., 2018). Meanwhile, more than 70 individual age determinations have been carried out, but no consensus on the true impact age could be achieved. Although the Ries age of is now known to roughly 1-2 % (Jourdan, 2012), its accurate age is still subject of intense discussion. For example, the high-precision date of 14.775 Ma suggested by Schmieder et al. (2018) was criticized by Rocholl et al. (2018) as being geologically impossible, mainly because it is at odds with paleomagnetic evidence.

Here, we show that a combination of various geological tools involving paleontological, paleomagnetic and orbital tuning data constrain the Ries impact at exactly 14.870 ± 0.005 Ma. Paleomagnetic data of Pohl (1977, 1978) indicate that the impact took place during a reversed chron time interval. Chrons of normal magnetization are therefore inconsistent. For the time window under discussion, either the reversed chrons C5Bn.1r (15.032-14.870 Ma) or C5ADr (14.775-14.609 Ma) are relevant. Additionally, Pohl (1977, 1978) concluded that the impact occurred concurrently with a switch from a reversed to a normal chron, i.e. at either the C5Bn.1n/C5Bn.1r or C5ADn/C5ADr chron boundary. These chron boundaries are astronomically tuned with extraordinarily high precision and accuracy of better 5 ka (ATNTS2012, Hilgen et al., 2012), thus pinning down the two possible impact ages at 14.870 Ma and 14.609 Ma, respectively. The paleomagnetic record of the crater lake sediments as well as the occurrence of the mammalia fauna MN6 in the upper part of the crater sediments unequivocally indicate that the Ries crater formed at 14.870 ± 0.005 Ma.

Talk

## Dynamics and solidification of different impact melt zones during peak-ring formation of the Chicxulub crater, Mexico

**Felix Magnus Schulte, Ulrich Riller**

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Drilling into the peak ring of the Chicxulub crater during IODP-ICDP Expedition 364 unveiled two thick zones of melt rock. The upper zone is 36 m thick and covers shocked granitoid target rock, whereas the lower zone is enveloped by target rock at a depth between 1220 and 1316 meters below sea floor. The zones differ in terms of layering, chemical composition, fragment content and crystallization. Yet, both are attributed to an impact melt origin, which begs the questions regarding their individual dynamics and solidification.

The upper melt rock zone can be divided into three subunits, which are form bottom to top: 1) A 9 m thick subunit consists of two aphanitic, fragment-poor silicate phases displaying mottled texture, evident by devitrified glass and plagioclase grain size. These observations indicate quenching and auto-brecciation during melt solidification. 2) A 16 m thick subunit consists of interlayered silicate and carbonate melt rock displaying convoluted centimeter-scale folds. Cusp-and-lobe geometry indicates that the silicate phase was more viscous than the carbonate phase during folding and solidification. 3) A 6 m thick melt breccia subunit is composed of carbonate melt rock displaying flow-textures and reaction rims on silicate melt rock fragments indicating that the silicate phase solidified first. By contrast, the lower melt rock zone consists exclusively of silicate melt rock mixed and mingled with, as well as entrained into, strongly brecciated target rock. The melt rock is made up by a holohyalin matrix of devitrified brown glass hosting angular to sub-rounded target rock fragments. At the margins to brecciated target rock, melt rock displays large contact strains through viscous deformation, evident by highly stretched fragments.

The structural characteristics of the upper melt rock zone point to incomplete separation of two compositionally different melt phases, driven by density contrast and intermittent shaking of the peak-ring during melt solidification. Structural observations of the lower melt rock zone suggest entrainment of rapidly cooling silicate melt into brecciated target rock slivers. Thrusting of target rock over surficial impact melt during peak-ring formation explains the observations. In summary, both melt zones agree with an impact melt origin.

Talk

## Geochemical constraints on the formation and origin of melt-bearing impact breccias: The Ries impact structure example

**Susann Siegert[1,2], Lutz Hecht[1,2], Michael J. Branney[3]**

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Melt-bearing impact breccias (so-called suevites) represent one of the most important lithological witnesses of impact cratering since they comprise target material from almost all stages of shock metamorphism, ranging from unshocked lithic fragments to highly homogenized impact melt fragments. The process of primary mixing of the various suevite components as well as the process of transport and deposition during cratering is still highly debated. Previous models of transport and/or deposition of Ries suevite were mainly focused on (1) fall back of material during collapse of an ejecta plume [1], (2) deposition via a density flow [2] or a lateral flow [3,4], (3) deposition from an impact melt flow [5], and (4) collapse of post-impact phreatomagmatic plume caused by fuel-coolant interaction (FCI) of an impact melt sheet with water [6].

We present new geochemical data including trace element analyses of all suevite components from several locations of the Ries crater. The immobile high field strength element contents show lateral and vertical variation of the suevite blanket. This heterogeneity has its origin in spatially controlled chemical variation of the crystalline basement of the target lithologies. However, the composition of the individual suevite components at each location or stratigraphic position is coherent, indicating well mixing of variously shocked material within certain sectors during cratering.

Emplacement of the suevite by density currents is mainly indicated by (1) topography-influenced (ponded) thickness variations of the suevite sheet, (2) very poor sorting and matrix support of particles, (3) massive nature, (4) subtle coarse-tail grading, (5) abundant elutriation pipes, and (6) an inverse-graded basal layer with low-angle cross-stratification.

The lateral chemical zoning as well as field and textural evidences are best explained by radial outflow of density currents. In addition, later convergence of flow paths probably allowed more thorough mixing of density currents in the crater. This is recorded by the more uniform composition of the later deposited upper parts of the crater-fill suevite [7].

References

[1] Engelhardt, W. v. et al. (1997). Meteorit. Planet. Sci. 32, 545-554. [2] Newsom, H.E. et al. (1990) Geol. Soc. Spec. Pap. 247, 195-206. [3] Bringemeier, D. (1994) Meteorit. Planet. Sci. 29, 417-422. [4] Meyer, C. et al. 2011. Geol. Soc. Am. Bull.123, 2312-2319. [5] Osinski, G.R. et al. (2004) Meteorit. Planet. Sci. 39, 1655-1683. [6] Stöffler, D. (2013). Meteorit. Planet. Sci. 48, 515-589. [7] Siegert, S. et al. (2017) Geology 45, 855-858.

Talk

## Remote Sensing Analysis and Landscape Evolution Modeling of the Bosumtwi Impact Structure, Ghana: Indications for Ejecta Ramparts

**Gerwin Wulf, Stefan Hergarten, Thomas Kenkmann**

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Impact crater formation and ejecta emplacement models of terrestrial impact craters are often compared with observations of lunar craters which are formed in dry targets and without atmospheric interaction, typically showing a blocky ejecta blanket with radial patterns and textures. In contrast, craters in volatile-rich environments often have layered ejecta blankets with ejecta ramparts, as seen for Martian impact craters. Based upon the terrestrial Bosumtwi crater, we use an innovative approach to get new insights in the impact crater formation process combining remote sensing and geomorphological analyses with landscape evolution models. In the process, we make a detailed remote sensing analysis of Bosumtwi crater, investigating the geology and geomorphology. This includes the morphometric analysis of watersheds and drainage pattern from Digital Elevation Models (DEMs), and the interpretation of multi-spectral image data. The results are compared with a fresh Martian impact crater of similar size for which a hypothetical drainage network and catchment areas were derived. Subsequently, we prove whether the current morphology of Bosumtwi crater can be the result of erosion of a typical Martian or lunar impact crater using landscape evolution modeling. Our results clearly show that the current morphology of Bosumtwi crater cannot be explained by erosional processes of a lunar-like impact crater. Instead, our results demonstrate that the morphological and spectral characteristics of Bosumtwi crater possess striking similarities to those of Martian rampart craters, especially to DLE craters. Therefore, we suggest that Bosumtwi crater was originally built as a Mars-like rampart crater and as a consequence that the current morphology is the result of a weakly eroded ejecta rampart. This means that Bosumtwi crater allows us to investigate and understand the rampart formation process that is of great importance for Martian impact craters, on the basis of a nearly pristine and easily accessible terrestrial impact crater.

# Topic 7: Mineralogy, material science of the Earth

## 7a) Advances and new applications in chemical, isotope and structural analysis

Talk

### U-Pb LA-ICP-MS dating of low-U minerals: A case study of high grade metamorphic garnet

**Richard Albert, Axel Gerdes, Leo Millonig, Linda Marko**

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Recent studies on relatively U-rich skarn garnet (*c.* > 2 ppm) have shown that garnet can be used as a chronometer using the *in situ* U-Pb LA-ICP-MS technique (*e.g.* Seman *et al.*, 2017, Deng *et al.*, 2017). However, garnet formed during metamorphic or magmatic processes commonly has sub-ppm concentrations of U (*c.* 1 to 300 ppb). This work discusses and investigates the complications of dating low-U garnet and highlights the potential and advantages of the method used.

Different reference synthetic glasses (NIST614/612), garnet, titanite and zircon were analysed to evaluate the effect of chemical composition and optical properties on the instrumentally induced U/Pb fractionation. Differences in U/Pb fractionation (after correcting for down-hole U/Pb fractionation by the intercept method) between zircon-garnet, NIST614-garnet and zircon-titanite are larger than between zircon-NIST614 and titanite-garnet, indicating that this fractionation is to a certain extent matrix induced (MIEF), inducing differential ionisation conditions in the Ar-plasma.

Several garnet crystals of known age and different compositions have been tested: 1) Almandine–pyrope rich garnet from a HP-HT potassic granulite (Plešovice). The obtained mean ages of 336 ± 10 Ma to 346 ± 12 Ma agree within uncertainty with the Plešovice zircon age of 337.13 ± 0.37 Ma (Sláma *et al.*, 2008); 2) Almandine-rich garnet from eclogites (Variscan Orogen, Cabo Ortegal Complex). Garnet U-Pb ages of 398 ± 20 Ma are within error of the inferred age of HP-HT metamorphism, constrained by zircon U-Pb dating at *c.* 390 Ma (Albert Roper, 2017).

This ongoing work shows that low-U garnet with variable amounts of common Pb is datable and therefore it is possible to date garnet formed in almost any geological scenario, including garnet-grade metamorphism.

Talk

### Applying stable isotope analysis to evaluate soil management techniques in agricultural field sites

**Anne E. Berns[1], Bei Wu[1], Yi Wang[1], Ying Xing[1], Roland Bol[1], Kathlin Schweitzer[2], Michael Baumecker[2], Wulf Amelung[1,3]**

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An increasing number of studies demonstrate the potential of using non-traditional stable isotopes as a tool to identify soil formation processes, to pinpoint translocation processes or to determine geologic sources, however, these ratios are rarely applied to agricultural systems to assess the impact of agricultural practices on nutrient cycling in soils. Studies show that the isotope composition of several nutrient elements may vary between top- and subsoil due to biogeochemical processes (1, 2). Agricultural soil management may alternate these variations in isotope composition, potentially leading to different isotope signatures in crop tissues due to nutrient uptake.

In this study, we present for the first time Mg isotope compositions in soil profiles (down to 100 cm) from a long-term field trial (> 90 years) in Berlin-Dahlem, Germany. The effect of long-term liming was assessed by analysing the isotope compositions of Mg pools in soil and plants. The soil d$^{26}$Mg values increased along the soil profile, showing a depletion of heavier Mg in the topsoil and an enrichment of heavier Mg in the subsoil. Magnesium in the non-limed fields was found to be isotopically lighter than that in the limed plots across all depths. Thus, the isotope signature could potentially yield significant information on elemental transports in soils and help to clarify important nutrient uptake processes by crops.

In another long-term field trial in Berlin-Thyrow, where irrigation practices have been applied over 50 years, we detected a depletion of light Fe isotopes in deeper soil horizons, while the plough horizons showed an enrichment in light Fe isotopes. By comparison, the non-irrigated plots displayed a relatively uniform isotope composition across all depths. These two studies confirmed that long-term agricultural practices can impact isotope composition of nutrient elements.

References:

(1) Fekiacova Z., Pichat S., Cornu S., Balesdent J., 2013. Geoderma 209-210, 110-118.

(2) Bolou-Bi E.B., Vigier N., Poszwa A., Boudot J.-P., Dambrine E.,2012. Geochimica et Cosmochimica Acta 87, 341–355.

Poster

## Iron reservoirs in a forested headwater catchment: stocks and isotopy

**Anne E. Berns[1], Nina Gottselig[1,2], Charlotte Seckfort[1,3], Dominik Hezel[4], Ying Xing[1], Carsten Münker[4], Wulf Amelung[1,2], Roland Bol[1], Bei Wu[1]**

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An increasing number of studies demonstrate the potential of Fe isotope ratios as a tool to identify soil formation processes, to pinpoint Fe translocation processes within soils and to determine the geologic source of Fe (1, 2). Fe isotope ratios of the suspended river load have recently been used to determine the geologic source of Fe in the Amazon river system (2) and the correlation of dissolved organic carbon (DOC)/[Fe] with $\delta^{56}$Fe of the dissolved load was identified as an indicator for authigenic Fe input (3).

The Wüstebach catchment is a small forested subcatchment located within the National Park Eifel at the outreach of the Rur catchment and is part of the TERENO Eifel/Lower Rhine Valley Observatory. The site is equipped with in situ sensors monitoring constantly a variety of parameters. At this catchment we aim to identify the magnitudes of different Fe stocks as well as sources and sinks of the Fe cycle. Evaluation of Fe concentration data revealed a stock of 33.6 t of plant available Fe (extracted with $CaCl_2$/pentatic acid) in the top 30 cm of soil. The total stock was estimated to be approx. 2770 t (extracted by pressurized microwave digestion) in the top 30 cm of soil. The vegetation consisted mainly of Norway spruce (90%). The Fe stock contained in the vegetation was estimated to be approx. 1.6 t. Monitoring of the Fe concentration in the stream water over 5 years revealed that, depending on hydrological conditions, the catchment loses between 18 and 57 kg dissolved Fe per year. First Fe isotope measurements of environmental samples (stream water, soil horizons, spruce needles and beech leaves) revealed a range of $\delta^{56}$Fe values from -1.82 to 0.78 ‰ (values relative to IRMM-14). Vegetation samples represent the lightest reservoir with values of -0.61 ‰ (spruce needles) and -1.82 ‰ (beech leaves). In contrast, soil samples ranged from -1.63 to 0.61 ‰ showing the effects of litter recycling in the top soil and redox variations in the subsoil, respectively. The stream water therewith represents a sink of Fe from different sources and liberation processes.

References:

(1) Fekiacova Z., Pichat S., Cornu S., Balesdent J., 2013. Geoderma 209-210, 110-118.

(2) Dos Santos Pinheiro, Poitrasson F., Sondag F., Cruz Vierira L., Martins Pimentel M., 2013. Journal of South American Earth Sciences, 44, 35-44.

(3) Chen J-B., Busigny V., Gaillardet F., Louvat P., Wang Y-N., 2014. Geochimica et Cosmochimica Acta 128, 128-143.

Poster

## U-Pb dating of hydrothermal vein agate using LA-ICP-MS

**Anika Braun, Frank Tomaschek, Markus Lagos, Thorsten Geisler**

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Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) is a novel method for U-Pb geochronology of cryptocrystalline silica varieties, such as chalcedony and agate. We applied this tool in an attempt to constrain the age of prominent hydrothermal vein deposits of the Erzgebirge, Germany. The Erzgebirge vein deposits are characterized by sequential groups of distinctive mineral associations (Kuschka 2002). The mineralization sequence formed during successive episodes of tectonically controlled hydrothermal activity, for which the available radiometric data suggests to span in time from the Permian to the Cretaceous (Romer et al. 2010).

We analyzed two fragments from the agate-amethyst vein of Schlottwitz (East Erzgebirge, Saxony), well known for their striking sequence of silica varieties. The mineralization sequence of both analyzed samples (SRF and SLW) was petrographically assigned to Kuschka´s *flq* sequential group. Polished slabs were characterized using optical microscopy, UV-fluorescence to detect uraniferous silica domains, electron back-scattered and cathodoluminescence imaging, as well as Raman spectroscopy. U-Pb isotope ratios were obtained by laser ablation (coupled to an Element 2/XR sector field ICP-MS) using standard-sample-bracketing with NIST 612 glass as primary reference material, and calibrated opal for method validation.

Measured isotopic ratios from uraniferous chalcedony of the main agate from sample SRF define a mixing line towards common lead in a Tera-Wasserburg diagram. Regression results in an intercept age of 289 ± 13 Ma, consistent with the expected Permian age for the *flq* sequential group. In addition, however, several spots on agate from sample SLW yield erratic apparent ages. Secondary disturbance seems to correlate with the presence of microcrystalline quartz layers, intercalated within chalcedony. In summary, the laser ablation technique can be used for U-Pb dating of chalcedony and agate. However, since the U-Pb system of agate might be compromised due to a replacement of chalcedony by quartz, combining a detailed characterization of silica varieties with spatially resolved isotopic analysis seems essential for the successful application of agate U-Pb geochronology.

**References**

Kuschka, E. (2002): Zur Tektonik, Verbreitung und Mineralogie sächsischer hydrothermaler Mineralgänge. Geoprofil 11, 1-183.

Romer, R.L., Schneider, J., Linnemann, U. (2010): Post-Variscan deformation and hydrothermal mineralization in Saxo-Thuringia and beyond: a geochronological review. In Linnemann, U., Romer, R.L. (eds) Pre-Mesozoic Geology of Saxo-Thuringia. Schweizerbart, 347-360.

Talk

## Carbon and oxygen isotope fractionation in the water-calcite-aragonite system

**Jens Fohlmeister[1,2], Jennifer Arps[3], Christoph Spötl[4], Andrea Schröder-Ritzrau[3], Birgit Plessen[2], Christina Günter[1], Norbert Frank[3], Martin Trüssel[5]**

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The precise determination of the stable C and O isotope fractionation between water and calcite (CC) and water and aragonite (AR) is of special interest for climate reconstructions, e.g. paleotemperatures. Previous studies reported results from both laboratory and field experiments, but their results are only partly consistent. Here we present C and O isotope data of a stalagmite from the Swiss Alps, which shows CC-AR transitions along individual growth layers. Using detailed analyses both laterally and perpendicular to such layers we examined the difference in the C and O isotope fractionation factor of the $HCO_3^-$ - CC and the $HCO_3^-$ - AR system. For O this difference is similar to the water-CC and water-AR offset provided in experimental studies. The O isotope fractionation difference in the water-CC and water-AR system is comparable to those determined in laboratory studies but shows a statistically significant correlation with the $CaCO_3$ precipitation rate. For C we found a fractionation difference, which is independent of $CaCO_3$ precipitation rate and with slightly smaller values for the fractionation offset between $HCO_3^-$ - CC and $HCO_3^-$ - AR compared to literature values. However, we also found an unexpected decrease in $\delta^{13}C$ along growth layers, which contradicts the widely used concept of Rayleigh fractionation during $CO_2$ degassing and $CaCO_3$ precipitation. The results of this study can be used e.g., to correct stable isotope time series of stalagmites showing CC-AR transitions along their growth axes.

Poster

## A Chondrite Analogue Nanoparticle Calibration Material for LA-ICP-MS

**Claudia Funk[1], Frank Wombacher[1], Daniel A. Frick[2], Thomas Meisel[3], Alexander Heuser[4], Andreas Kronz[5], Detlef Günther[6]**

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A custom-tailored nanoparticle powder with major and minor element (except K and V) and Se and Te abundances similar to CI chondrites has been prepared for use as calibration material for LA-ICP-MS analyses of chondritic meteorites. The nanoparticle powder, abbreviated CAN for chondrite analogue nanoparticles was produced by flame spray synthesis and pressed into a 13 mm pellet [1]. For comparison, another fine-grained powder pellet has been prepared from the CM2 chondrite Cold Bokkeveld (COBO) by wet-milling [2]. Elemental compositions for both materials have been determined by various measurement principles.

The homogeneity of the CAN and COBO powder pellets and NIST SRM 612 glass was assessed based on Al-normalized signals obtained from ten one mm laser line scans using ~80 µm beam width. For CANS, the elemental homogeneity is about similar or superior to that of NIST SRM 612. Thus, CAN powder pellets are of suitable homogeneity for calibration in LA-ICP-MS. Several elements in COBO, however, proved to be heterogeneously distributed (e.g. W, Ca and S) due to imperfect pellet preparation and contamination during our first attempt with natural samples.

CAN and NIST SRM 612 were then utilized for the quantification of major and trace elements in an Allende CV3 chondrite thick section. To minimize elemental fractionation, fs laser ablation was applied. Difficulties for the ablation yield correction related to the erratic small-scale heterogeneity of chondritic materials were overcome by internal normalization to the sum of major and minor element compounds.

[1] Tabersky, D., N.A. Luechinger, M. Rossier, E. Reusser, K. Hametner, B. Aeschlimann, D.A. Frick, S.C. Halim, J. Thompson, L. Danyushevsky, D. Günther (2014) Development and Characterization of Custom-Engineered and Compacted Nanoparticles as Calibration Materials for Quantification Using LA-ICP-MS. *J. Anal. At. Spectrom.* 29:1364–5544.

[2] Garbe-Schönberg, D. and Samuel Müller. (2014) Nano-Particulate Pressed Powder Tablets for LA-ICP-MS. *J. Anal. At. Spectrom. 29:990-1000.*

Poster

## LA-ICP-MS microanalysis of iodine, bromine and chlorine in fluid inclusions

**Tobias Fusswinkel[1], Christopher Giehl[2], Oliver Beermann[3], Johan Rafael Fredriksson[4], Dieter Garbe-Schönberg[3], Lea Scholten[3], Thomas Wagner[1]**

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Halogen ratios in hydrothermal fluids are only weakly affected by fluid-rock interaction processes and hence represent excellent tracers of the source reservoir. In recent years, in-situ LA-ICP-MS microanalysis of chlorine and bromine in individual fluid inclusions has provided fundamentally new insight into hydrothermal fluid flow and ore forming processes. However, depletion or enrichment of halogens relative to chlorine in the fluid source reservoirs can be caused by other processes than seawater evaporation or halite dissolution, which cannot be unequivocally discriminated on the basis of Br/Cl ratios alone. Iodine concentration data provide an additional constraint allowing to discern between selective and coupled halogen enrichment processes, but low concentrations and a lack of suitable reference materials have precluded quantification of iodine in fluid inclusion LA-ICP-MS microanalysis so far.

We present the first combined Cl-Br-I concentration data determined by LA-ICP-MS analysis of fluid inclusions using the established Sca17 scapolite standard reference material for external standardization. The robustness and accuracy of the method was verified using synthetic fluid inclusions of known compositions, which were prepared at 600 °C and 100 / 200 MPa in cold-seal pressure vessels from four different starting solutions containing Na, Rb, Cs, Br and I. The iodine concentrations measured in the synthetic fluid inclusions are in excellent agreement with the reference concentrations (determined by ICP-OES and ICP-MS analysis of the starting solutions). Average iodine concentrations in inclusions synthesized from a 27 µg/g iodine starting solution were 27.3 ± 3.9 µg/g (14.3% RSD), and 77.6 ± 6.4 µg/g (8.3% RSD) in inclusions synthesized from a 78 µg $g^{-1}$ iodine solution. Chlorine and bromine reference concentrations were also reproduced to better than 10% and 20% RSD, respectively.

The method was subsequently applied to natural samples in a pilot study on sample material from several hydrothermal veins (Alpine metamorphic quartz veins, an Archean orogenic gold deposit and post-Variscan Pb-Zn and Mn-Fe vein deposits). In all cases, chlorine, bromine and iodine could be quantified successfully. Significant differences in terms of Br/Cl and I/Cl ratios underline the potential of the method in discerning between coupled evaporative halogen enrichment and selective bromine and iodine enrichment via interaction with organic matter in the fluids' source regions. The addition of iodine to the analytical toolset of fluid inclusion LA-ICP-MS microanalysis thus opens up exciting new possibilities in furthering our understanding of crustal fluid flow processes.

**Talk**

## Reference materials for microbeam sampling: Where do we stand?

**<u>Dieter Garbe-Schönberg</u>[1], Samuel Müller[1], Simon Nordstad[2], Leewe Schönberg[2], Michael Wiedenbeck[3], Axel D. Renno[4], Maxim Portnyagin[5], Thomas Zack[6], Dany Savard[7]**

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for the direct elemental and isotopic analysis of solid materials has undergone continuous and significant improvement over recent years, development of well-characterized and homogeneous microanalytical reference materials (MRM) for calibration and validation of micro-analytical data has been delayed. Actually, the deficiency of matrix-matched MRM hampers the acceptance, and wider application, of microbeam techniques.

Ideally, MRM must be homogeneous down to the micrometer scale for major, minor, trace, and ultra-trace elements and isotopes, withstand high-vacuum and the impact of high-energy photon, electron, and ion beams, stable in its physical and chemical properties over time and under various environmental conditions, certified following ISO guidelines, and available for a wide variety of materials. There are few individual MRM available as natural minerals meeting the specific needs of certain geochemical applications (e.g., U/Pb age dating) but their availability and quantities are limited. For many rock forming minerals, especially sulfides, suitable MRM are extremely rare in nature, and difficult to synthesize. Some vitrified materials and synthetic glasses are widely used but are not truly matrix-matched to minerals leading to analytical bias. Moreover, many materials are difficult, or impossible, to vitrify without the addition of a flux that dilutes the original material and bears the risk of contamination. A promising approach are nano-particulate pressed-powder pellets that can be produced from almost any (brittle) material.

A new method has been developed for manufacturing undiluted, binder-free pressed powder pellets[1]with particle grain size down to the nanometer range ($D_{50}$<170 nm), extremely low roughness of pellet surface ($R_A$ <50 nm), and excellent within- and between-pellet homogeneity. This method has been applied so far to a wide range of very different sample types: feldspar, mica for Rb/Sr age-dating[2] , refractory minerals (graphite!), iron ores and banded iron formation, manganese nodules, sulfides, bone-apatite, biogenic carbonates (foraminifera, clam shells, corals), speleothem, ultra-mafic to acidic plutonic and volcanic rocks, fly ash etc.. We blended materials opening new ways for producing coherent series of elemental and isotopic calibration standards. These "nanopellets" have been successfully used with LA-ICP-MS, LIBS, µ-XRF, p-XRF, and EPMA, PIXE, SIMS. In addition, this way of sample preparation bears the potential of completely replacing conventional tedious and hazardous wet-chemistry procedures for bulk analysis, and this holds true in particular for refractory samples like ceramics, granites, ultramafic rocks, and samples with easy-to-contaminate or volatile components that would be lost during acid digestion or vitrification.

[1 ] *JAAS,*29,990 (2014); [2] *JAAS*,32,305(2017

Talk

## Tin isotope composition of geological reference material and natural samples using double spike MC-ICP-MS

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Tin is a key element for understanding planetary processes, like core segregation, crust formation or volatile addition. Tin has 10 stable isotopes, with a relative mass range of ~10 % between $^{112}Sn$ to $^{124}Sn$. Furthermore, Sn is present in two main oxidation states ($Sn^{2+}$, $Sn^{4+}$). These properties lead to the expectation of resolvable Sn isotope fractionation during geological processes. In order to shed new light on the Sn isotope composition of terrestrial silicate reservoirs we performed a comprehensive study of 13 geological reference materials along with a selection of MORB, IAV, and mantle samples. We used a $^{117}Sn$-$^{122}Sn$ double spike, for which the optimal composition and spike-sample ratio were calculated using the ´double spike tool box´ (1). Calibration was performed using the method of (2). Sample digestion and ion-exchange separation followed the protocol of (3).

Tin isotopes were analysed using a ThermoFinnigan Neptune MC-ICP-MS at the joint Cologne-Bonn facility operated in static mode. We measured isotopes $^{116}Sn$ to $^{124}Sn$, as well as $^{125}Te$ and $^{126}Te$ for interference correction. The inversion and all subsequent data reduction was performed using a custom-made *Mathematica®* code following the method of (1). In general, high-T settings show enrichment of heavier isotopes with a range from $\delta^{117/122}Sn$= -0.57 ± 0.23 ‰ (n=5) for BIR 1 to $\delta^{117/122}Sn$= -0.35 ± 0.19 ‰ (n=19) for BG 49 (in-house basalt standard). Low-T settings vary in Sn isotope composition but may display $\delta^{117/122}Sn$ up to +6.89 ± 0.01 ‰ for e.g., Fe-Mn nodules.

Our results show that large Sn isotope fractionation occurs during high- and low-T processes. Redox transformation of Sn seems to be a dominant process responsible for Sn isotope fractionation. Collectively, Sn isotope systematics opens up new possibilities to investigate planet-building and crust-forming processes and potentially tracking paleo-redox conditions through time.

1) Rudge et al., 2009. The double spike toolbox. Chemical Geology 265 (2009) 420–431.

2) Kurzweil et al., 2018. Accurate stable tungsten isotope measurements of natural samples using a $^{180}W$- $^{183}W$ double-spike. Chemical Geology 476 (2018) 407–417.

3) Kirchenbaur et al., 2018. Determination of In and Sn Mass Fractions in Sixteen Geological Reference Materials by Isotope Dilution MC-ICP-MS. Geostandards and Geoanalytical Research, Vol. 42, No. 2 (2018).

Poster

## Ti investigations of the Earth and Moon

**Sebastian Kommescher[1], Raúl O. C. Fonseca[1], Maxwell M. Thiemens[1], Carsten Münker[1], Peter Sprung[2,1]**

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Titanium isotopes are valuable tracers of the nucleosynthetic heritage of planetary bodies. For example, Ti isotope variations (expressed as $\delta^{49}Ti$) can be used to characterize magmatic processes taking place in planetary interiors. The observation that $\delta^{49}Ti$ correlates with $SiO_2$ content makes Ti isotopes a useful tool in investigating the onset of plate tectonics, and provides evidence for a felsic crust existing 3.5 Ga ago.

A high purity $^{47}Ti$ and $^{49}Ti$ double spike was calibrated and tested against reference materials from the Origins Lab in Chicago (OL-Ti) and from the University of Cologne. We modified a previously set up chemical purification scheme to separate Ti and High Field Strength Elements from sample matrix. Very good separation between matrix elements, Hf, Zr, W, Mo, and Ti is achieved without dry-down steps. An additional clean-up chemistry allows us to eliminate the remaining isobaric interferences (e.g. Ca, Cr, and V). Measurements were performed with a Neptune Plus MC-ICP-MS coupled to an ESI APEX HF and additional glassware.

Nucleosynthetic studies of lunar samples yield long term reproducibility below 0.1 ε-units (10 ppm, 2 s. d.) for our in-house reference material. Our $\varepsilon^{50}Ti$ data reveal neutron capture effects that correlate well with epithermal and thermal neutron capture monitors $\mu^{180}Hf$ and $\varepsilon^{149}Sm$ for low-Ti mare basalts, some KREEP-samples and between different landing sites, in particular Apollo 15 and 17. After correction for secondary neutron capture reactions, the Silicate Earth and lunar samples show no resolvable differences. Double spike analysis of the OL-Ti and the Köln-Ti reference materials result in an external reproducibility around 0.09‰ (2 s. d.). Double Spike analysis of JB-2 agrees well with published data.

Poster

## New micro-analytical reference materials

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While *in-situ*analytical instrumentation for the direct elemental and isotopic analysis of solid materials has undergone continuous and significant improvement over recent years, development of well-characterized and homogeneous micro-analytical reference materials (MRM) for calibration and validation of analytical data has been delayed. The main issue with producing MRM for a wide range of natural and technical materials is reaching sufficiently low heterogeneity on the micrometre scale both within and between individual splits. Ultra-milling of materials to nanoparticles provides an efficient way of re-homogenization and brings particle sizes well below the beam diameter of most micro-analytical techniques, hence accomplishing stoichiometric sampling of heterogeneous poly-phase materials.

A further advantage of ultra-milling includes the mechanical breakdown and homogenous redistribution of accessory minerals (e.g. zircon, spinel) that may not be fully digested by acids. This makes ultra-milling a safer and less time consuming way of sample preparation for subsequent bulk-analyses. Processing of analytical grade powder (<75 µm) into a nano-particulate pressed powder pellet takes two days instead of a whole week in the wet-chemistry lab with hazardous chemicals.

We processed a large variety of geochemical reference materials into “nano-pellets”[2]following ISO guidelines. These pellets have been successfully analysed with LA-ICP-MS, LIBS, SIMS, EPMA, and µXRF[Office1] making them a universal multi-method MRM. Our portfolio, so far, includes ultramafic to siliceous rocks, carbonates and phosphates, iron and copper ore, manganese nodules, coal fly-ash, and minerals (i.e. feldspar, mica). Currently, we have apatite, magnetite, and copper ore concentrate under development as certified MRM. Customized MRM meeting the needs of individual applications can be produced on request. So far, the pressed pellets are available in 13 and 32 mm diameter.

Here we present new data on grain-size distributions, surface properties, minimal sampling-mass and uncertainties, and accuracy of results for major to ultra-trace elements and isotopes. A planned project is the development of isotopic and elemental compositional series for instrument calibration by blending nano-powders from different endmembers.

[1] Garbe-Schönberg D. & Müller S., *JAAS,*29, 990 (2014)

[2] www.my-standards.com

**Poster**

## Titanite U – Pb geochronology of the Evje-Iveland Pegmatite Field, Norway

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The Evje-Iveland Pegmatite Field in southern Norway went through a complex geological evolution, starting with pegmatite intrusions into the ~1 Ga old metamorphic basement of the Telemark domain followed by different stages of metasomatic and/or hydrothermal overprints. However, almost nothing is known about the age of these distinct events. This project aims to unravel their relative and absolute ages using U-Pb dating of titanite by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

Based on field observations, three different geological events have already been identified [1]. The mineral assemblage of the magmatic stage is dominated by K-feldspar, biotite, muscovite, quartz, and subordinately plagioclase. Titanite from the Evje pegmatite locations Einerkillen, a former uranium mine, and Rossås are assigned to this magmatic stage and occur as particularly large crystals with several centimeters in size. As part of a later metasomatic overprint amazonite and clevelandite were formed in several pegmatites. We did not sample individual titanite crystals of this stage. However, magmatic titanite samples show replacement rims that we assign to this metasomatic overprint. The last event was a hydrothermal overprint, which formed assemblages including epidote, albite, and idiomorphic quartz in cavities. Such paragenesis is well documented in the Landsverk I pegmatite [1]. Here, titanite occurs as small aggregates with only a few millimeters in size.

First LA-ICP-MS U-Pb data yield an age of 918 ± 14 Ma for the magmatic titanite, overlapping with a U-Pb age of 910 ± 14 Ma of gadolinite from an unknown location in the Evje-Iveland Pegmatite Field [2]. The U-Pb analyses of the alteration or replacement zones around the magmatic titanite suggest that the metasomatic stage took place shortly after the magmatic stage, supported by similar U-Pb ages determined for the igneous titanites and their replacement products. Preliminary data for the hydrothermal titanites from Landsverk I suggests that this stage is completely unrelated to the pegmatite emplacement, but can be correlated with the Caledonian orogeny that likely triggered the formation and movement of hydrothermal fluids in the Telemark domain. In conclusion, U-Pb dating of titanite from the different locations is well suited to unravel the different geological stages of the Evje-Iveland Pegmatite Field.

[1] Müller et al. 2017: *NGF Geological Guides 6*, 48-85

[2] Scherer et al. 2001: *Science 293*, 683-686

**Talk**

## Potential of in-situ presolar grain isotopic analyses using a collision cell MC-ICPMS, Proteus

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Many problems in geology and cosmochemistry are nowadays tackled with isotopic and elemental analyses on the micron scale. However, accurate *in-situ* laser ablation isotope analyses are often compromised by molecular and isobaric interferences. The next generation collision cell MC-ICPMS Proteus offers unique opportunities to suppress interferences or to promote the analyte away from perturbing species while maintaining the analytical capabilities of a MC-ICPMS [1,2].

Meteorites and their components are known to exhibit mass-independent isotope anomalies, which are related to deficits or excesses of distinct stellar sources [3]. These variations in primitive meteorites are assumed to be related to ad- or unmixing of (sub-)µm-sized presolar grains, representing the smoking gun of the nucleosynthetic heritage of our Solar System and tracing earliest processes in the protosolar nebula. Some of these nucleosynthetic signatures in bulk meteorites could be linked to certain types of presolar grains [3], however, the relatively large anomalies (several parts in ten thousands) in heavy isotopes of Ca and Ti, $^{48}Ca$ and $^{50}Ti$, remain enigmatic [4,5].

*In-situ* presolar grain studies were limited to sophisticated instrumentation and typically to low-mass elements [6]. Especially $^{48}Ca$ and $^{50}Ti$ suffer from their relative low abundance and isobaric interferences, namely $^{48}Ti$, $^{50}Cr$, and $^{50}V$. Proteus offers new capabilities to accurately resolve anomalies of these isotopes and to search for phases carrying the nucleosynthetic signatures. Oxygen, as a reaction gas, is able to promote more than 90% of $Ti^+$ to $TiO^+$, while reacting $Ca^+$ only at the per mil level to its oxide species, thus, efficiently separating the two elements. Other isobaric interferences ($^{50}Cr$, $^{50}V$) are only somewhat suppressed but can accurately be corrected for. The preceding quadrupole allows selection of a mass range entering the reaction cell, from hundreds of atomic masse to single isotopes. Interestingly, this revealed reproducible mass-independent oxygen isotope ratios of oxide species after $TiO^+$ formation of the single Ti isotopes.

This contribution reports on the progress in method development for Laser ablation mass-independent isotope measurements of Ti with Proteus with emphasis on the specific behaviour of the reaction cell system.

References: [1] Elliott et al. (2015) Goldschmidt 25, Abstract #824. [2] Chen et al. (2016) Goldschmidt 26, Abstract #427. [3] Dauphas & Schauble (2016) Annu. Rev. Earth Planet. Sci. 44, 709. [4] Chen et al. (2011) ApJ, 743, L23. [5] Davis et al. (2018) GCA 221, 275. [6] Floss & Haenecour (2016) Geochem. J. 50, 3.

Talk

## Mineralogy meets Energy: Insights from TEM-EELS to Performance and Ageing of Mn and Fe based Layered Oxide Materials used as Battery Cathode Material

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The demand to store energy not only for portable electronic devices but also for large scale applications (grid storage) fosters the development of new battery concepts seeking for low cost/high abundance elemental resources. However, the transfer of structural concepts from well-established lithium ion to sodium based batteries requires modification to balance e.g. capacity and cycling performance. Sodium-transition metal (TM) oxides ($NaTMO_2$) containing Mn and Fe are promising candidates as cathode materials [1] which do not have direct mineral analogs but typical structural units of layered Mn oxides (e.g. birnessite) and variable layer stacking schemes (like sheet silicates). Understanding the operation and limiting factors in charge and discharge cycles need an advanced analytical approach that combines structural and chemical changes including the detection of valence states.

Here, $Na_{2/3}[Mn_{3/5}Fe_{2/5}]O_2$ synthesized by a sol-gel method was tested by galvanostatic charge-discharge cycling in two potential ranges of 2.0-4.2 V and 1.5-4.2 V in Na-ion half cells using Na foil as the counter and reference electrodes. Transmission electron microscopy (TEM) and electron energy loss spectroscopy (EELS) were used among other methods to gain insights into the capacity fading mechanism.

Based on EELS the pristine material has a charged balanced formula of $Na^+_{0.66}Mn^{4+}_{0.57}Fe^{2+}_{0.05}Fe^{3+}_{0.33}[]_{0.05}O_2$. It exhibits an initial capacity of about 130 mAh $g^{-1}$ when cycled at 15 mA $g^{-1}$ in the potential range of 2.0-4.2 V. The capacity decreases only to about 80 % capacity after 100 cycles which makes it a potential cathode material for Na-ion batteries. When cycled in the potential range of 1.5-4.2 V, a higher initial capacity of about 150 mAh $g^{-1}$ is found, but it retains only about 60 % capacity after 100 cycles. TEM and EELS analyses of cycled materials show the formation of two secondary phases at the rim of the layered oxide with spinel (solid solution of hausmannite and magnetite) and layered (birnessite-like) structures along with a change in the oxidation states of transition metals. The structural conversion effectively blocks the re-sodification by interlacing the octahedral transition metal layers. The amount of these secondary phases is larger for the sample cycled between 1.5-4.2 V, indicating that their formation is an important ageing mechanism. Such „alteration“ or „weathering“ pathways involving crystal chemical reactions are well-known in mineralogy and may encourage to integrate mineralogical knowledge to an important applied and socio-econonic topic.

References: [1] P. K. Nayak, L. Yang, W. Brehm, P. Adelhelm, Angew. Chem. Int. Ed. 2018, 57, 102.

**Talk**

## Trends of OH-defect incorporation in experimentally grown quartz at crustal conditions

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Quartz is one of the most important nominally anhydrous minerals and the second most abundant rock-forming mineral in the Earth's crust. Due to its large stability field, quartz is a major constituent in magmatic, metamorphic and sedimentary rocks as well as in unconsolidated material. Quartz incorporates trace elements in the crystal structure via coupled substitutions of trivalent ($Al^{3+}$, $B^{3+}$, $Fe^{3+}$) and monovalent ($H^+$, $Li^+$, $K^+$, $Na^+$) cations, depending on the crystallisation conditions in different geological environments. Hence, quartz is reasonably used as a tracer for crystallisation conditions. In this experimental study we focus on the incorporation of OH-defects in quartz from granitic systems. To simulate realistic conditions for the emplacement of granitic magmas in the upper crust, piston cylinder (PC) and internally heated pressure vessel (IHPV) synthesis experiments were performed in the water saturated granitic system at 1 – 5 kbar and 600 – 950 °C. All starting materials consisted of powdered natural granite doped with additional quartz powder and 12 – 18 wt% $H_2O$. Successful runs consisted of a free aqueous fluid, amorphous quench material and quartz crystals, as well as accessory phases in varying amounts. Sufficiently large quartz crystals (> 100 µm) were manually orientated and polished to thin wafers parallel to the c-axis. Two polarised FTIR measurements per crystal were conducted on the same spot, one $\parallel n_e$ and one $\parallel n_o$, to separate the strongly polarised OH-defect signal from the isotropic $H_2O$ signal of fluid inclusions. IR absorption bands can be assigned to specific OH-defects and discriminated qualitatively and quantitatively. Crystal homogeneity in terms of OH-defect content was verified by FTIR-imaging of one particular crystal. Preliminary results show: 1) the AlOH band triplet around 3310, 3378 and 3430 $cm^{-1}$ is the dominating absorption feature in all spectra, 2) the LiOH-defect band at 3470-3480 $cm^{-1}$ increases strongly with pressure, 3) the total OH-defect content increases with pressure in the range of 3 kbar (125 wt ppm $H_2O$) to 4.5 kbar (500 wt ppm $H_2O$), which is in contrast to a recent experimental study in a similar system between 5 to 20 kbar, where decreasing OH-defect contents with increasing pressure were observed. Thus, the current data suggest the existence of a maximum in OH-defects in quartz between 4 and 5 kbar. The experimental findings are going to be applied to natural environments, e.g., to gain additional information on the differentiation history of particular plutonic bodies.

**Talk**

## *In situ* analyses of Li isotopes in olivines from volcanic rocks with femtosecond laser ablation MC-ICP-MS

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Kinetic isotope fractionation, e.g. driven by diffusion, plays an important role in high-temperature environments. Isotopic zoning in magmatic minerals caused by diffusive processes is frequently used to determine cooling rates of igneous rocks by diffusion modeling. Recent examples comprise Fe-Mg chemical and isotopic zoning in olivines (Sio et al. (2013), Oeser et al. (2015)). Lithium appears to diffuse much faster than Fe-Mg in many geological materials and thus it can be used to determine more short-lived processes (Dohmen et al. (2010)). Lithium fractionates only little during crystallization (Tomascak et al. (1999)) but diffusion may generate isotopic variations of up to 40 ‰ within single grains (Jeffcoate et al. (2007)). However, in order to determine time scales of volcanic processes using Li, crystals with low Li concentrations have to be measured precisely with high spatial resolution, in order to resolve diffusion profiles.

Here, a new method for the analysis of Li isotope ratios at low concentrations in magmatic minerals (2-20 ppm Li) has been developed. A femtosecond laser ablation (fs-LA) system is combined with a MC-ICP-MS, because of its ability to facilitate essentially matrix-independent *in situ* isotope analyses. MC-ICP-MS analyses were performed with relatively cool plasma and an optimized detector ensemble, which is adapted to the achieved signal intensities. This setup enables the determination of $\delta^7Li$ values with an accuracy of ~2 ‰ at a few ppm Li concentration. The latter has been proven by cross-calibrating our laser ablation data to solution-analyzed $\delta^7Li$ values of standard reference glasses from previous studies. Olivines have been measured by fs-LA and for cross-calibration by solution MC-ICP-MS, both *in situ* and bulk solution datasets are in good agreement.

Diffusion profiles of major elements, trace elements and Li isotope ratios in olivine crystals from several sample locations (Canary Islands, Massif Central) have been determined and show that fs-LA is suitable to achieve a sufficient spatial resolution (<50 µm). For basanite olivines from Tenerife and a basanitic olivine from the Banne D'Ordanche (Massif Central) the Li concentration appears to be coupled to the trend of Mg#. Preliminary results suggest that Li isotope ratios are coupled to Li concentrations in most cases. Furthermore, we will investigate the relation of previously determined Fe-Mg isotopic zoning and Li isotope variations. With these findings it will be possible in future to draw conclusions on Li diffusivity in olivine in general and thus the applicability of Li as a reliable geospeedometer.

# 7b,c) Minerals and materials: Properties and structures

Poster

## Characterization of germanium-/silicon mullites in the solid-solution series ($SiO_2$,$GeO_2$)-$Al_2O_3$

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Mullite is an alumino-silicate forming chains of edge-sharing $AlO_6$ octahedra parallel [001]. According to a variety of thermo-mechanical properties such as low thermal expansion and conductivity as well as high fracture toughness and strength, it is a promising material for structural and functional ceramics. In this study the substitution of silicon by germanium in mullites was performed by using sol-gel methods.

According to the general formula $^{VI}Al_2^{3+}\,^{IV}Al_{2+2x}^{3+}\,^{IV}M_{2-2x}^{4+}\,O_{10-x}$ (where M represents either Si, or Ge), we were able to synthesize a complete range in solid solution between the two endmembers Si-mullites and Ge-mullites. For this purpose, $GeO_2$, $SiC_8H_{20}O_4$ (Tetraethyl orthosilicate, TEOS) and $Al(NO_3)_3$ * $9H_2O$ were used as starting materials for the sol-gel method. The gel was calcined at 1300°C for 2h. Powder samples were investigated by X-ray diffraction and scanning electron microscopy. EDX analysis showed that Si was gradually replaced by Ge. The mullite phases crystallized in the orthorhombic space group *Pbam*, and showed a significant volume expansion with increasing germanium content. The observed lattice parameters range from $a$ = 7.5519(1) Å, $b$ = 7.6949(1) Å, $c$ = 2.88531(4) Å for the silicon end member to $a$ = 7.6440(1) Å, $b$ = 7.7868(1) Å, $c$ = 2.93122(2) Å for the germanium end member. In-situ HT-XRD measurements are in progress for the determination of thermal stability and thermal expansion.

Poster

## Radiation-damage-induced transitions in zircon: Percolation theory and the mechanical properties

**Tobias Beirau**[1], **William D. Nix**[2], **Rodney C. Ewing**[3], **Herbert Pöllmann**[1], **Ekhard K.H. Salje**[4]

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We followed the radiation-damage process in zircon ($ZrSiO_4$) by careful analysis of changes in the mechanical properties using nanoindentation (Beirau et al. 2018). From this, evidence can be provided for percolation transitions occurring around 30% and 70% amorphous fractions, which is in excellent agreement with the finding in literature (Salje et al. 1999, Geisler et al. 2003, Trachenko et al. 2004, and Salje 2006). Our presented results provide an independent confirmation of measurements that were made by other techniques that are sensitive to different length scales. At the percolation points, the indentation hardness has found to deviate from its linear correlation with the elastic modulus, the shear modulus and the bulk modulus. Both percolation points generate anomalies in the hardness versus density evolution.

Beirau, T., Nix, W.D., Ewing, R.C., Pöllmann, H., and Salje, E.K.H. (2018) Radiation-damage-induced transitions in zircon: Percolation theory applied to hardness and elastic moduli as a function of density. Appl. Phys. Lett. 112, 201901.

Geisler, T., Trachenko, K., Rios, S., Dove, M.T., and Salje, E.K.H. (2003) Impact of self-irradiation damage on the aqueous durability of zircon (ZrSiO4): Implications for its suitability as a nuclear waste form. J. Phys.: Condens. Matter 15, L597–L605.

Salje, E.K.H. (2006) Elastic softening of zircon by radiation damage. Appl. Phys. Lett. 89, 131902.

Salje, E.K.H., Chrosch, J., and Ewing, R.C. (1999) Is “metamictization” of zircon a phase transition? Am. Miner. 84, 1107–1116.

Trachenko, K., Dove, M.T., Geisler, T., Todorov, I., and Smith, B. (2004) Radiation damage effects and percolation theory. J. Phys.: Condens. Matter 16, S2623–S2627.

Poster

## Macroscopic and nanoscopic phenomena of the metamict state - titanite and pyrochlore

**Ulli Bismayer**[1], **Peter Zietlow**[1], **Tobias Beirau**[2], **Ekhard Salje**[3], **Lee Groat**[4], **Boriana Mihailova**[1], **Pierre Toledano**[5]

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Metamict minerals show radiation-induced structural disorder caused by the alpha-decay of radionuclides which are incorporated in their structure. The metamictization occurs over geological times in different steps forming inhomogeneous crystal phases with a) low degree of damage with localized defects and amorphous embryos surrounded by crystalline material, b) increased amorphous clusters which may percolate and c) small crystalline domains embedded in an amorphous matrix (Toledano & Bismayer 2005). It had been shown that thermal annealing often leads to restoration of the crystalline order depending on the level of structural damage (Ewing 1994).

Macroscopic (volume swelling, glass-like surface, hardness etc.) as well as local phenomena (different susceptibility of structural units to damage accumulation, interfaces, distribution of Fe2+/Fe3+ in amorphous and crystalline regions etc.) have been observed. Experimental studies of titanite and pyrochlore are presented to compare selected local with mesoscopic/macroscopic phenomena (Beirau et al. 2018; Zietlow et al. 2017).

References

Toledano P. and U. Bismayer (2005). Phenomenological therory of the crystalline-to-amorphous phase transition during self irradiation. J. Physics: Condensed Matter 17, 6627 - 6634.

Ewing R.C. (1994) The metamict state: 1993 – the centennial. Nucl. Instrum. Meth. B, 91, 22-29.

Tobias Beirau, Dawid Murawski, Harald Behrens, Ekhard K H Salje, Lee A Groat, Ronny Kaden, Herbert Pöllmann and Ulrich Bismayer (2018). Locally preserved α → β phase transition in natural radiation-damaged titanite (CaTiSiO5): Evidence from laser-induced photoluminescence and dielectric measurements. Journal of Physics: Condensed Matter, 30, 035403 (8pp).

Peter Zietlow, Tobias Beirau, Boriana Mihailova, Lee A. Groat, Thomas Chudy, Anna Shelyug, Alexandra Navrotsky, Rodney C. Ewing, Jochen Schlüter, Radek Škoda and Ulrich Bismayer (2017). Thermal annealing of natural, radiation-damaged pyrochlore. Z. Kristallogr. 232, 25-38.

Talk

## High-temperature reactions in the anhydrite-quartz system studied by in situ hyperspectral Raman imaging

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During the combustion process of lignite, the deposition of mineral phases on heat transfer surfaces have a negative effect on power plant boilers. Such ash deposition, including fouling and slagging, reduce the heat conductibility and consequently the efficiency of the power station. The temperature at which sintering reactions take place strongly depends on coal composition. Therefore, it is important to determine the chemical and phase composition of brown coal before burning it. Modern confocal Raman spectrometer systems with integrated heating stages, allow the ‘visualization’ of mineral distribution and textures even at high temperatures with a spatial resolution of a few micrometers. Therefore, it is an exceptional method to follow high-temperature phase transformations *in situ*.

In the present study, samples consisting of the typical minerals of Rhenish lignite ash anhydrite, quartz, and gehlenite, were fired to about 1100°C and the reactions were analyzed *in situ* by hyperspectral Raman spectroscopy. The aim was to visualize phase reactions between these minerals and gain kinetic and thermodynamic information about mineral growth and breakdown. In order to use mineral phases as temperature indicators for the combustion of lignite, it is necessary to understand their behavior at high temperatures. Taking into account all calcium phases that can potentially form during firing, different weight and molar ratios of the raw materials were used for the experiments. Of particular interest was to investigate the formation of wollastonite and dicalcium silicate as a function of the quartz content in the anhydrite-quartz system.

The sintering experiments revealed relevant insights to calcium silicate mineral reactions: (i) At about 830°C gehlenite recrystallized to wollastonite. (ii) At temperatures higher than 920°C, wollastonite formed by the reaction between quartz and lime, the latter which was provided by the thermal decomposition of anhydrite to CaO and $SO_2$. In those experiments, where less quartz was available, wollastonite formed first at about 1000°C, indicating that the quartz content influences the decomposition of anhydrite and thus the crystallization of wollastonite. (iii) At 1100°C the crystallization of $\alpha'_L$-$Ca_2SiO_4$ was observed. During the cooling process, $\beta$-$Ca_2SiO_4$ (larnite) crystallized and remained metastable at RT. It follows that (iv) quenching has a significant effect on the interpretation of sintering experiments. Such information and information about the mechanism(s) of solid-solid transformations are essential to predict sinter reactions at high temperature in, e.g., brown coal blocks. In general, *in situ* studies are necessary to reconstruct the temperature-time histories of naturally or technically sintered materials.

Poster

## Interlayer water increases high-pressure $CO_2$ sorption capacity of SWy-2 Montmorillonite

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In the context of geologic sequestration of carbon dioxide the interaction of $CO_2$ with minerals is an important process. Considerable amounts of this gas can be stored by physisorption on rocks, such as shales and coal. The $CO_2$ storage capacity usually decreases in the presence of water due to competitive sorption.

Smectitic clays have high gas sorption capacities but they also take up considerable amounts of water, leading to volumetric expansion depending on their interlayer cations (e.g. $Na^+$ or $Ca^{2+}$). It is therefore important to understand the behaviour of this system upon exposure to supercritical $CO_2$.

In this study, we performed high-pressure $CO_2$ adsorption experiments on expandable clays ($Na^+$ and $Ca^{2+}$-exchanged SWy-2 Montmorillonite) in the dry state and different hydration levels at P-T conditions relevant for $CO_2$ sequestration (up to 20 MPa, 45°C).

The excess sorption isotherms, determined by the manometric method, exhibit maxima at bulk $CO_2$ densities between 200 and 500 kg $m^{-3}$ (7.4 to 10 MPa $CO_2$ pressure), followed by a linear decrease. For both expandable clays the maximum excess sorption capacity was found to increase significantly with increasing interlayer water up to the moisture equilibration level of 32% relative humidity (RH). The maximum $CO_2$ sorption capacity of the SWy-2 Na-montmorillonite increased from 0.48 mmol $g^{-1}$ for the dry sample to 0.63 mmol $g^{-1}$ after equilibration at RH 32% ($H_2O$ uptake: 3.7 wt %). For the Ca-exchanged SWy-2 the sorption capacity almost doubled from 0.52 to 0.97 mmol $g^{-1}$ (11.4 wt % $H_2O$ uptake at RH 32%). At hydration levels above 32 % RH the $CO_2$ excess sorption capacity decreased.

The observed behaviour appears to be closely linked to the structure and swelling properties of these clays in the presence of $CO_2$. According to Giesting et al. (2012a, b) dry montmorillonite hardly expands when exposed to $CO_2$. However, a shift in the mean basal spacing $d_{001}$ between the hydrated clay layers upon exposure to $CO_2$ occurs when the initial water content increases. Our excess sorption data are in line with infrared light absorption measurements by Lohring et al. (2014) indicating that the $CO_2$ impact is strongest at moderate water contents and peaks around the 1W hydration state. This indicates that high-pressure $CO_2$ adsorption is strongly influenced by the intercalation of $CO_2$ into the expandable interlayers, which, in turn is controlled by hydration.

Talk

## POLARIO, a computer program for calculating refractive indices from chemical compositions

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Refractive indices $n$ are routinely used to describe the properties of minerals and other transparent compounds. POLARIO (Fischer et al. 2018) is a computer program to calculate mean refractive indices of minerals and compounds from their chemical composition and molar volume $V_m$. Up to 32 elements can be entered. The program uses the Anderson-Eggleton relationship (Anderson 1975; Eggleton 1991; Shannon and Fischer 2016)) to calculate $n$ from the total polarizability $\alpha_{AE}$ derived from the sum of the contributions of the ions to the polarizability taken from Tables 4 and 5 in Shannon and Fischer (2016). In the second approach, the mean refractive index is calculated from the sum of the refractive energies (Gladstone-Dale constants) according to Mandarino (1976, 1981). Alternatively, a subset of Gladstone-Dale constants for silicates can be taken from Eggleton (1991).

If measured refractive indices or observed polarizabilities are entered, POLARIO also allows calculation of the deviation between observed and calculated values and determines the compatibility index (Mandarino 1979, 1981) as a measure of agreement. Atom parameters can be read in cif format to determine possible coordination numbers of cations and to compose the entire input necessary to do the calculations. It displays a table of interatomic distances and angles, and it shows the chemical composition with superscripted coordination numbers and valencies. The program does not contain polarizability values for uranyl ions and for ions having lone-pair electrons ($Tl^+$, $Sn^{2+}$, $Pb^{2+}$, $As^{3+}$, $Sb^{3+}$,$Bi^{3+}$, $S^{4+}$, $Se^{4+}$, $Te^{4+}$, $Cl^{5+}$, $Br^{5+}$, $I^{5+}$) which do not fit the simple additivity scheme of polarizabilities. Compounds that are ion conductors, generally alkali-ion rich, typically show calculated refractive indices, $<n_D>$, 0.7-3% larger than observed refractive indices. Compounds containing edge- and corner-sharing octahedra (M = $Fe^{3+}$, $In^{3+}$, $Y^{3+}$, $Ti^{4+}$, $Nb^{5+}$, $Ta^{5+}$, $V^{5+}$, $Mo^{6+}$, and $W^{6+}$) typically show calculated refractive indices, $<n_D>$ of 5-30% smaller than observed refractive indices.

The program is written in Delphi XE6 for WINDOWS operating systems and contains 5,300 constants and parameters to do the calculations.

Acknowledgements: We thank the DFG for funding this project under grant FI442/21-2

References:

Anderson, O.L. (1975) Fortschritte der Mineralogie, 52, 611-629.

Eggleton, R.A. (1991) Canadian Mineralogist, 29, 525-532.

Fischer, R.X., Burianek, M., Shannon, R.D. (2018), American Mineralogist, in press (DOI 10.2138/am-2018-6587)

Shannon, R.D., Fischer, R.X. (2016), American Mineralogist, 101, 2288-2300.

Mandarino, J.A. (1976) Canadian Mineralogist, 14, 498-502.

Mandarino, J.A. (1979) Canadian Mineralogist, 17, 71-76.

Mandarino, J.A. (1981) Canadian Mineralogist, 19, 441-450.

Talk

## *In-Situ* Characterization and Thermal Decomposition Behavior of Ammonium-Exchanged Chabazites

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Ammonium-exchanged zeolites, where the $NH_4^+$ ion represents the charge-compensating cation, play an important role as precursor materials in the production of H-zeolites. The hydrogen zeolites can be used as catalysts with their protons acting as Brønsted acid sites. Here, we present results on ammonium-exchanged natural chabazite within the framework of a project studying the mechanisms of deammoniation processes in zeolites *in situ* to produce the H-forms acting as catalysts.

Single crystals and powder samples of natural Ca chabazite (Locality: Aranga Quarry, North Island, New Zealand) with chemical composition $Ca_{2.2}[Al_{4.4}Si_{7.6}O_{24}]\cdot 12H_2O$ were $NH_4$ exchanged. EDX and FTIR analyses showed that essentially all Ca was exchanged by $NH_4$ for both single crystal and powder samples. Powder-diffraction experiments indicate a slight change in the lattice parameters upon ammonium exchange.

*In situ* TG-MS-IR analyses for $NH_4$-CHA showed 3 mass-loss steps accomplished at 220°C, 540°C, and 640°C, which are interpreted as dehydration, deammoniation, and dehydroxylation processes, respectively. The thermal evolution of $NH_4$-CHA was further assessed with *in situ* high-temperature X-ray diffraction experiments using a Paar HTK1200 heating chamber within a range from 25°C (room temperature) up to 660°C. Detailed evaluation of the data is in progress.

Single-crystal diffraction data were collected for Ca-CHA at 25°C and for NH4-CHA at 25°C, 260°C, and 560°C. The crystal structures were refined for all data sets in space group $R\bar{3}m$ in hexagonal setting. At 560°C the crystal structure was determined to be protonated chabazite. The relative stabilities of different proton sites were investigated using density-functional theory (DFT) calculations.

Lattice parameters were recorded at 25 °C, 260 °C, and 560 °C yielding decreasing $a$ and increasing $c$ upon heating.

Talk

## The Werkendam drillings: A natural analogue for rock interaction with supercritical carbon dioxide $scCO_2$ and correlated changes of petrophysical properties

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Changes of porosity, permeability, electrical conductivity and finally the E-modul were studied on sandstone samples from the Werkendam drillings, the Netherlands. WED2 ($CO_2$-free) and WED3 ($CO_2$-rich). are separated by a fault, but intersect the same geological setting. Densities cover the range from <2.7 g/cm³ up to >2.8 g/cm³. Porosities of the untreated samples range from 0.3% up to 16.5%, permeabilities from <0.01 mD up to >160 mD. Significant differences between samples from well WED2 and WED3 were not detected. Subsequently, in total 8 samples from wells WED2 and WED3 were used in experimental series with supercritical $CO_2$ ($scCO_2$) performed at pressures of 10-12 MPa and temperatures ranging from 100 up to 120°C. The samples were saturated with an artificial brine (0.1 M NaCl) in a desiccator. In a first step the autoclave experiments lasted about 45 days, samples were then taken out and were analyzed again. In a second series they were exposed to the same pressure and temperature conditions thus resulting in a reaction time of about 120 days. Porosity exhibited a slight increase for both sets of samples. Permeabilities of the WED3 samples was more or less unchanged, while the WED2 samples exhibited a more complicated figure by showing an increase, a decrease and unchanged permeability. The frequency dependent complex electrical conductivity (SIP) was measured in the frequency range $10^{-3}$ Hz up to 45 kHz. The interpretation of the complex conductivity data revealed a set of bulk-conductivities that correlate with permeability. Low frequency data provide information on fluid/solid interactions at the inner surface of the pores. These data will be published separately. Unfortunately two of the samples failed in the experimental series. In a final sequence the uniaxial compressive strength and E-modul were measured on untreated and processed samples. Thus we could get an estimate on weakening of the mechanical stability caused by $scCO_2$-treatment.

Poster

## Microstructures of pyrite studied by Electron Back Scatter Diffraction (EBSD)

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Pyrites ($FeS_2$) are frequent sulfides in sedimentary, metamorphic as well as magmatic rocks forming characteristic growth patterns during their formation. The microstructural development of pyritic assemblages from different geological settings have been studied by FE-SEM. Aim of the study has been the comparison between local textural development of individual idiomorphic pyritic assemblages formed at different growth conditions. The electron optical studies have been carried out in a Field-Emission Scanning Electron Microscope (FEI Quanta 200) equipped with a CCD camera to study the orientation contrasts along the surfaces of pyrite. Local textures of the pyrite studied result mainly from growth and minor from shear deformation. The studied samples derived from Navajun (Spain), Greece, China and Cape Blanc Nez (France) and the assemblages studied comprise pure pyrites without any intergrowth of pyrrhotites.

The examined crystals of pyrite show different crystal orientations and orientation contrasts resulting from domains of smaller misorientations within larger pyrite crystals can be resolved. In a three-dimensional pyrite sphere a polygonal structure of pyrite grains in the core and fibre texture in the edge can be resolved. The orientations of the crystal fibres show internal misalignments of 5° to 15°, which is the <100>-sliding system, as described by Barrie et al (2008). The orientations of individual pyrite fibres indicate preferred crystal growth at a low nucleation rate. The <100>- sliding system is dominant, but there are other sliding systems as well showing higher misalignment.

In pyritic ammonites studied, primary fossil structures like e.g., ammonitic sutures, influence the nucleation, crystal growth and the habit of the newly formed pyrites. Within pyritized ammonites, newly grown fibrous textured pyrites fills the phragmocone. As part of a sulfate-sulfide reaction, relicts of barium sulfate is present as educt minerals in these chambers. Other ammonites studied show a replacement of the shale by newly formed pyrite resulting in an intense intergrowth of grains of calcite and pyrite. EBSD measurements indicate a polycrystalline microfabric of both minerals, still reflecting primary structures of the ammonites e.g., the Septen.

EBSD studies show, that local microstructures of idiomorphic pyrite in the samples studied reveal a correlation between nucleation rate and following growth rate of the individual pyrites, thus leading to the characteristic crystal habits.

Barrie et al. (2008), Mineral. Mag. 72 (6), S. 1181–1199. DOI: 10.1180/minmag.2008.072.6.1181.

**Talk**

## “Sillimullite” – a new mineral species intermediate between sillimanite and mullite

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A new mineral intermediate between sillimanite and Si-rich mullite introduced as “sillimullite“ by Fischer et al. (2015) has been further characterized to approve this mineral as a new species. Therefore, one acicular single-crystal from the Ettringer Bellerberg, Eifel volcanic fields, Germany, has been investigated by single-crystal X-ray diffraction methods, electron microprobe analysis, and the spindle-stage method to determine the refractive indices. Furthermore, an X-ray powder diffractogram has been acquired from another sample of the same locality. The electron microprobe analysis yields the following chemical composition $Na_{0.010}Mg_{0.048}Al_{8.55}Fe_{0.29}Si_{3.14}Ti_{0.02}O_{19.633}$ (assuming that all Fe is trivalent) corresponding to an $x$-value of 0.18(8). The composition derived from the crystal-structure refinement is $Al_{8.23}Fe_{0.29}Si_{3.49}O_{19.743}$ corresponding to $x$ = 0.129(3). The obtained mineral formulas can be described by the compositional series $M^{+}_{y}M^{2+}_{z}M^{3+}_{8+4x+y+2z}M^{4+}_{4-4x-y-2z}O_{20-2x}$. The difference of both compositions results from the chemical inhomogeneity of the crystal. The composition derived from the refinements represents the average of the compositional range of the individual microprobe analyses. “Sillimullite” is orthorhombic, *Pnam*, with $a$ = 7.5432(5) Å, $b$ = 7.7048(5) Å, $c$ = 5.7965(3) Å, $V$ = 336.89(6) Å³, $Z$ = 1. Its crystal structure follows the same Si/Al ordering scheme at tetrahedral sites like sillimanite but the neighboring dicluster chains of $SiO_4$ and $AlO_4$ tetrahedra have an offset of ½ **c**. At the same time the crystal structure shows the formation of oxygen vacancies and tetrahedral triclusters as it is known for the crystal structure of mullite. Crystal-structure refinements converged to $R_{(obs)}$ = 3.46 % for 664 unique reflections [$F_o > 3\sigma(F_o)$]. Fe almost exclusively enters the octahedral sites. The concentrations of Ti, Mg and Na are so low, that they did not affect the refinement. Refractive indices are $n_x = n_y$ =1.668 (4) and $n_z$ = 1.680 (4) measured in white light; 2V = 34 (5)°; the optical orientation is $X \parallel \mathbf{a}$, $Z \parallel \mathbf{c}$. The powder diffractograms of sillimanite and “sillimullite” are very similar. They only may be distinguished from each other by their 011/101 and their 231 reflection. The reflection 011 of “sillimullite” has an intensity of about 20 % of that of the 101 sillimanite reflection and the 231 peak barely appears in the “sillimullite” diffraction pattern. “Sillimullite” possesses features of both minerals sillimanite and mullite. Nonetheless its crystal structure is distinctly different from both and must therefore be considered as a new discrete mineral species.

**Poster**

## Multiscale dissolution rate investigation on the same olivine (0 1 0) surface

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One of the most promising methods to reduce carbon emissions in the cement and concrete industry is enhancing the belite hydration, which is chemically analog to the hydration of Mg-olivine (forsterite). The dissolution rate is a key indicator of aqueous reactivity and is relevant in predicting the process of hydration and property development of the material.

It is advised to use Vertical scanning interferometry (VSI) and Atomic Force Microscope (AFM) to study the dissolution rate of olivine on the same surface with the identical experimental condition. The surface of the olivine crystal is identified by XRD to determine the crystal face is (0 1 0). After embedding, polishing, and masking, the sample is fixed on the sample holder and the dissolution experiment is performed and detected in the in-situ AFM reaction cell and fluid cell for Raman-enhanced VSI characterization. HCl solutions with different pH and ultra-pure water (resistivity>18MΩ/cm) are used in the experiments. By recording the topography evolution, dissolution rates are calculated from height changes of the surface topography and can be described by rate maps and dissolution rate spectra. In addition, Raman spectroscopy is used to determine the chemical change in composition during the experiment. Time-lapse results could shed light on the dissolution kinetics of olivine (0 1 0) surface.

**Poster**

## The VAsCo project – an integrated experimental approach to investigate the chemical interaction of volcanic ash with thermal barrier coatings of jet engine turbines

**Dirk Müller[1], Kai-Uwe Hess[1], Gerhard Wolf[2], Pawel Rokicki[3], Volodymyr Palchyk[2], Donald Bruce Dingwell[1]**

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The injection of volcanic ash into a jet engine can cause several damage, leading to increased maintenance costs and in worst case to an in-flight outage of the engine itself. Due to the lack of a profound knowledge about the interaction of volcanic ash with a jet engine at the time when the iclandic volcano Eyjafjallajökull erupted in 2010, commercial flights had to stop for several days. In order to close this gap of knowledge, various experiments were carried out from researchers and engineers all around the globe. For these experiments, mainly a synthetic ash equivalent of calcium-magnesium-aluminum-silicon oxide (CMAS) and / or test sands were used. However, these standard aviation hazard test materials behave substantially different from natural ash. Clearly, the use of natural volcanic ash in such studies represents an improvement.

In the framework of the CORNET research project VAsCo ("Volcanic Ash resistant thermal barrier Coatings for jet engines" – www.vasco-cornet.eu) we use five different volcanic ashes, which represent the chemical range of possibly produced ash by explosive volcanic eruptions. The investigated thermal barrier coatings (TBC's) are atmospheric plasma sprayed (APS) and electron-beam physical vapor deposited (EBPVD) coatings of yttria-stabilized zirconia (YSZ) and gadolinium zirconate (GZO) as state-of-the-art materials. Both materials exhibit significantly different reactions in contact with a silicate melt, making them good candidates to study the influence of various volcanic ashes: While YSZ EB-PVD coatings are prone to be fully infiltrated by molten silicates, GZO exhibits a higher resistivity against the infiltration through a rapid re-precipitation of the dissolved coating, thus closing the pathways of infiltration.

The experiments are based on static and dynamic experiments: Static experiments include measurements with the heating microscope, to study the wetting and spreading of the molten ash sample on the TBC surface, and muffle furnace experiments with ash covered TBCs to study their chemical interactions. For dynamic experiments we thermally spray the ash on the TBC surfaces in order to simulate real conditions within the combuster/turbine section of a jet engine.

**Poster**

## Impacts on composition and thermal behavior of zeolite A (LTA) by extended washing with pure water – preliminary results

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A powder sample (#1) of well-crystallized zeolite A (particle size (1.3±0.4) µm) was synthesized according to [1]. The chemical composition (from XRF) is $Na_{12.02}Al_{11.99}Si_{12.01}O_{48}·25.5H_2O$ (Si/Al ratio= 1.001, water content determined by LOI and TG).

Two portions of the synthesized powder were extensively washed with a) pure water (sample #2) and b) aqueous 0.01 M NaOH solution (#3), respectively. Sample #3 did not display any change in composition compared to #1. After washing, sample #2 had a composition of $Na_{11.35}Al_{11.97}Si_{12.03}O_{48}·23.8\ H_2O$ (Si/Al= 1.005), i.e., a net charge imbalance of -0.62. This may possibly be explained by a partial exchange of $Na^+$ by $H_3O^+$ ions.

Rietveld refinements [2] based on XRPD data at 600°C confirmed a slightly lower $Na^+$ content for sample #2 (11.05(5)) than for #1 (11.33(5)) and #3 (11.34(5)), confirming the trend in the XRF data. However, for all samples the refined numbers of Na atoms were smaller than the expected value of 12. Notably, also here the values of as-synthesized sample #1 and the NaOH-treated #3 agree perfectly, i.e., washing zeolite A with 0.01 M NaOH solution prevents degradation of the sample on washing. The best matching model yielded much more water molecules (#1 39(1), #2 41(1), #3 40(2)) than expected (max. 27) so that conclusive results on a potential $H_3O^+$ - $Na^+$ exchange could not be established, despite the reasonable trend.

OES analyses of the liquids ("washing water") showed that after extensive washing to near neutral pH value of ~7.5 and less, more aluminum and silicon is released than at higher pH values. This is interpreted as the beginning of zeolite dissolution.

Furthermore, series of high temperature powder XRD measurements were performed on the three samples and refined in *Fm-3c*. Microstructural parameters of #2 ($H_2O$ washed) evolved strongly different from #1 and #3, somehow anticipating the observed differences in decomposition behaviors. The framework geometry was studied in high detail at ambient and high temperatures and the depletion of specific $H_2O$ positions could be nicely related to TG data. The dehydrated phase at 600°C finally agreed perfectly with results from literature [3].

The significantly different $Na^+$ and $H_2O$ contents from XRF-LOI-TG- versus Rietveld-based analyses remain an open issue for future work.

[1] R.W. Thompson (1982). J. Cryst. Growth 1982, 56(3), 711-722

[2] J. Birkenstock, T. Messner, R.X. Fischer (2018). BRASS2. University of Bremen, Geowissenschaften

[3] J.J. Pluth, J.V. Smith (1980). J. Am. Chem. Soc. 1980, 102, 4704-4708

Talk

## Kontrolle der Belagsbildung bei der Verfeuerung rheinischer Braunkohlen in Kraftwerkskesseln

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Im Rheinland werden jährlich knapp 100 Mio t Braunkohle zur Produktion von Strom, Wärme und Veredlungsprodukten eingesetzt. Beim Verbrennungsprozess kann es im Kraftwerkskessel zu den Betrieb behindernden Mineralreaktionen in Form von Belägen auf Wärmetauschern kommen, die es zu beherrschen gilt. Die hierfür erforderlichen thermochemischen Grundlagen wurden in mehreren Jahrzehnten gemeinsamer kontinuierlicher Forschung zusammen mit Hochschulen und Forschungszentren erarbeitet und in betrieblich umsetzbare Regeln für die Kohlegewinnung und ihren Kraftwerkseinsatz gebracht. Entsprechend der in den Braunkohlen enthaltenen Minerale und weiterer Parameter lassen sich rheinische Braunkohlen in 16 unterschiedliche Sorten unterteilen, die pur oder in Mischung den für sie jeweils best geeignetsten Anlagen zugeführt werden. Hierbei ist die Sicherstellung einer hohen Brennstoffqualität von hoher Bedeutung. Bereits eingesetzt oder erprobt werden zur Zeit drei unterschiedliche radiometrische Verfahren zur Online-Bestimmung der Gehalte der wichtigsten aschebildenden Kohle-Inhaltsstoffe. Hierzu gehören die Röntgenfluoreszenzanalyse, die prompte Gamma Neutronen Aktivierungsanalyse sowie das Gamma-Absorptionsverfahren.

Stark vereinfacht sind die Kohlesorten je nach Mineralstoffgehalt und -zusammensetzung so einzusetzen, dass eutektisch niedrig schmelzende Aschezusammensetzungen möglichst vermieden werden, um im Verbrennungsprozess die Bildung von Sintern und Schlacken zu verhindern. Ebenfalls wichtig sind die den belagsbildenden Mineralreaktionen zuzuordnenden Temperaturen, die über die Kesselfahrweise gesteuert werden können.

Mit Hilfe der im Beitrag gezeigten und in betriebliche Regeln umgesetzten wissenschaftlichen Erkenntnisse der physikalisch-chemischen Zusammenhänge ist es gelungen, eine fast vollständige Nutzung der Lagerstätte bei gleichzeitig höchster Kraftwerksverfügbarkeit zu erreichen.

Poster

## Mechanical and structural properties of radiation-damaged allanite-(Ce)

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Given the increasing interest in secure long-term disposal of actinides (e.g., from nuclear power plants), the understanding of the influence of nuclear radiation on condensed matter becomes more and more important. Analysis of naturally occurring U and Th containing minerals that received radiation exposure over geological time scales, can help to understand the related effects on the chemical and physical properties [1]. For the first time, detailed studies of the mechanical properties of the mineral allanite-(Ce) will be presented. Through the resulting α-decay of naturally incorporated radioactive elements the allanite structure has been damaged and the long-range order destroyed. Step-wise thermal annealing leads to recrystallization and decomposition that alter the structural properties. The behaviour of the hardness and elastic modulus was investigated by means of nanoindentation. Additionally, EMPA, IR and powder XRD measurements will be presented.

[1] Ewing et al. (1988) Nuc. Instr. Met. Phy. Res. B 32, 487–497

Talk

## A high-pressure structural analysis of $AlSiO_3OH$ Phase Egg

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Aluminiumsilicates, such as $AlSiO_3OH$ Phase Egg, are known to be stable at higher temperatures as their Mg-endmember equivalents. Therefore they are considered to play an important role for the transport of hydrogen into the deep mantle. We present the first high-pressure single-crystal x-ray diffraction study on Phase Egg. High-pressure structure refinements to a maximum pressure of 23.3 GPa have been performed. Phase Egg has a monoclinic $P2_1/n$ structure consisting of corner-sharing silicon- and aluminum-octahedra columns. A distortion of the Si-octahedron at ambient conditions was previously reported in a powder diffraction study by Schmidt et al. 1998. In the here presented study, we could identify a symmetrization of this Si-octahedron with pressure due to a massive compression of the Si-O4 bond, until a regular coordination is reached at ~15 GPa. This change in compression of the Si-octahedron can be associated with a stagnation of the β-angle to 98.7° observed at about the same pressure conditions. The b-lattice direction was identified as the most compressible, despite being the shortest. This can be related the orientation of the Si-$O_4$ bond and the void spaces in the structure. The compressional behavior of the unit-cell volume was fitted to a third-order Birch-Murnaghan equation of state yielding the following parameters: $V_0$ = 214.1(2)

Å³, $K_0$ = 153(8) GPa and $K_0$' = 8.6(13). The bulk modulus at ambient conditions is similar to the one measured by a powder-diffraction study (Vanpeteghem et al. 2003), but the pressure derivative found in this study is larger. Our study suggests that the symmetrization of the Si-octahedron is an important mechanism in compression behavior and structural evolution of Phase Egg below 15 GPa.

Schmidt et al. 1998, Synthesis, crystal structure, and phase relations of AlSiO3OH, a high-pressure hydrous phase, American Mineralogist, Vol. 83, p. 881- 888

Vanpeteghem et al. 2003, Compressibility of phase Egg AlSiO3OH: Equation of state and role of water at high pressure, American Mineralogist, Vol. 88, p. 1408-1411

**Talk**

## *In situ* Hyperspectral Raman Imaging: A new Method to investigate Solid-Solid Reactions in Ceramic Materials during Firing

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In the last decades Raman spectroscopy became an important tool to investigate minerals, gases, glasses, and organic material at room temperature. In combination with high temperature and high pressure devices the in situ investigation of mineral reactions and transformations became also possible. Here, we present a novel method to study the sintering process in silicate ceramics by in situ hyperspectral Raman imaging. We demonstrate that solid-solid phase transitions can be studied in situ at high temperature and thereby spatially resolved, providing completely new possibilities to study high-temperature solid-solid reactions in multi-component systems. Thermodynamic and kinetic phenomena can be studied without the need to quench the sample before analyzing the phase relations. In the present study, hyperspectral Raman spectroscopic imaging has been applied to *in situ* study the sintering process in the system $CaO-Al_2O_3-SiO_2$. Confocal micro-Raman spectra were recorded with a Horiba Scientific HR800 Raman spectrometer equipped with a 2W Nd:YAG laser (532.09 nm) and an electron-multiplier CCD detector. The samples were subsequently fired with a heating rate of 10°C/min (50°C steps) from about 700°C to 1200°C. At each temperature step one to several hyperspectral Raman images (100 x 100 µm, 1 µm step size) were recorded within a dwell time of 4 to 24 hours. The counting time varied between 0.6 to 1.3 s per pixel, which resulted in total imaging exposure times between about 2 to 4 hours. A Classical least squares (CLS) fitting procedure with house-intern reference spectra was used to obtain the relative phase proportions. The hyperspectral Raman images were created by false-colouring each pixel of the image relative to the fraction of each component in the spectrum. Three application examples will be presented to show (i) the effect of quenching, (ii) the investigation of the migration of a solid-solid reaction front at a micrometer scale, and (iii) the semi quantitative estimation of relative mineral fractions from which kinetic information can be gained.

**Poster**

## Two-phase mullites derived from fluorotopaz treatment and 3:2 mullite originating from combustion buchites

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Mullites are aluminosilicates with general composition $Al_2[Al_{2+2x}Si_{2-2x}]O_{10-x}$. Synthetic mullites in ceramics usually have x= 0.25 ($Al_2O_3$:$SiO_2$= 3:2), melt-grown synthetic mullites x= 0.4 (2:1). Only recently, the first detailed single-crystal structure analyses of natural mullite crystals showed that the minerals represent Si-rich members of the compositional series containing Fe and Ti as foreign cations [1].

With 35.0(6) wt% mullite is one of the major phases in our natural sample originating from combustion buchites (Durham Ranch, Wyoming, USA), besides cristobalite 45.1(13) wt%, quartz 9.0(2) wt%, feldspar 4.2(2) wt%, and gypsum 0.17(5) wt%. The $Al_2O_3$ content based on the refined lattice parameter $a$= 7.5375(3) Å (regression curve in [2]) is 59.67(4) mol%, i.e., $Al_2O_3$:$SiO_2$= 2.959(5):2.

Rietveld refinements of fluorotopaz-derived mullite ([3], sample A undoped, B doped with MgO, C with $Nd_2O_3$) with BRASS2 [4] revealed two distinct mullite phases, m1 and m2, in each sample. For sample A (w(m1)= 68.6(12) wt% , w(m2)= 31.4(8) wt%), the $Al_2O_3$ contents are 63.48(8) mol% (m1) and 58.43(16) mol% (m2) from $a$(m1)= 7.5639(1) Å and $a$(m2)= 7.5289(2) Å. Independently, constrained site occupation factor (SOF) refinements yielded roughly the same compositions: x(m1)= 0.328(12) and x(m2)= 0.180(12), corresponding to 63(2) (m1) and 57(4) mol% (m2) $Al_2O_3$. The weighted average of the four results is 61.5(6) mol%. Similar results, yet with less extreme differences for the two phases, were obtained for samples B and C.

A crystal from sample A (size ~0.15x0.05x0.02 mm³) was evaluated by single crystal diffraction using JANA2006 [5]. The composition derived from $a$ = 7.5446(6) is 60.8(5) mol% $Al_2O_3$, the one from the SOF-based x = 0.0697(3) is similar, 61.2(3) mol%. Being close to the weighted average in powder sample A we infer that the two mullites probably exist in small domains of the same crystal.

We thank Prof. K.T. Faber (NW University, Evanston, IL/USA) and Gunnar Färber (Samswegen, Germany) for providing the samples, and the DFG for funding (grant FI442/24-1).

[1] S. Lenz, J. Birkenstock, L. A. Fischer, W. Schüller, H. Schneider, R. X. Fischer (2018), Am. Min., submitted

[2] R.X. Fischer, H. Schneider & D. Voll (1996), J. Eur. Cer. Soc. 16, 109-113

[3] C.-H.H. Hsiung, A.J. Pyzik, E.B. Gulsoy, F. De Carlo, X. Xiao & K.T. Faber (2013), J. Eur. Cer. Soc. 33, 1955-1965

[4] J. Birkenstock, T. Messner, R.X. Fischer (2018). BRASS2. University of Bremen, Geowissenschaften

[5] Petříček, V., Dusek, M. & Palatinus, L. (2014), Z. Kristallogr. 229, pp. 345–352

**Poster**

## Detecting Co2 flow in porous media by electrical resistivity method

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Monitoring and detecting CO2 flow and possible leakage in the potential sites for Enhanced Oil Recovery (EOR) methods or Carbon capture and sequestration (CCS) is always a big concern for environmentalist and politicians and subsequently a big obstacle for implementing carbon capture and sequestration (CCS) at a large scale and reducing CO2 amount in the atmosphere. In this research we have done 40 flow through experiments on 4 different sandstones rocks with different permeability ranges in order to investigate the in situ electrical resistivity changes that caused by the CO2 in the samples. Formation index from Archie's law calculated and plotted versus saturation for different group. The results show the relationship between original permeability, injection time and brine salinity with the electrical resistivity properties. Even though further experiments are necessary and the results in this step is not conclusive but they confirmed that electrical resistivity method is a very good way to monitor and track the CO2 flow from the start of the injection and in situ measuring of formation factor and brine saturation condition and other petrophysical properties of reservoir rocks.

**Poster**

## In situ hyperspectral Raman imaging of the high-temperature sintering reactions in calcite-kaolinite mixtures

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The sintering process of kaolinite and calcite is well studied in literature because of its significance in ceramic industry. The mineral reactions in a calcite-kaolinite mixture during high-temperature firing have previously been studied by *in situ* HT-XRD experiments [1]. Common XRD experiments, however, deliver mineralogical information only for the bulk composition of quenched samples.

In the present study, confocal hyperspectral Raman imaging has been utilized to *in situ* study the sintering process of calcite and kaolinite with a weight ratio of 1:1, basically following the study of Stange et al. [2]. The samples were fired in a Linkam TS1500 heating stage from about 660°C to 1110°C with a heating rate of 10°C/min with temperature steps of 100°C. Raman spectra were recorded at each temperature with a Horiba Scientific HR800 Raman spectrometer equipped with a 2W Nd:YAG laser (532.09 nm) and an electron-multiplier CCD detector. After recording a Raman image at high temperature the sample was cooled to room temperature with a cooling rate of 10°C/min and another Raman image was recorded from the same region to study the effect of quenching. Hyperspectral Raman images were recorded with a 1 µm pixel spacing using a 50x LWD objective. With a counting time of 1 s per pixel, the total exposure time for a 150 x 150 µm-sized image was about 7 hours.

At about 660°C kaolinite was completely dehydroxylated. At this temperature calcite started to decompose to CaO and $CO_2$. During the subsequent cooling calcite recrystallized from CaO and atmospheric $CO_2$. We point out that in ex situ experiments this observation would not be possible and could lead to false interpretation of the calcite decomposition temperature. The decomposition begun at 660 °C with calcite domains still present and was completed at about 750°C. Furthermore, the formation of gehlenite in the sample quenched from about 930°C to room temperature could be observed in the area, where calcite was present before. With increasing temperature, the growth of gehlenite expanded into the kaolinite rich area.

Our preliminary data is encouraging and suggests that i*n situ* hyperspectral Raman imaging is a powerful method for *in situ* investigations of phase transitions, solid-solid reactions, and recrystallization processes at grain boundaries that take place during the thermal treatment of ceramic precursor materials.

[1] Ptáček et al. (2013) *Solid State Science* **26**, 53-58

[2] Stange et al. (2018) *J. Amer. Ceram. Soc*. **101**, 897-910

# Topic 8: Climate change, climate dynamics and paleoclimate

## 8a) Groundwater and climate change

Talk

### A groundwater climatology over Europe applying the Terrestrial Systems Modeling Platform, TerrSysMP

**Carina Furusho[1], Klaus Goergen[1], Jessica Keune[2], Ketan Kulkarni[1], Bibi Naz[1], Wendy Sharples[3], Stefan Kollet[1]**

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In order to evaluate the impact of climate change on groundwater resources, a climatology of groundwater states and fluxes over large spatial scales is required. Arguably, a consistent groundwater climatology is impossible to derive from measurements alone, because of scarce and often inconsistent observations, which are dispersed between many different national and international research and governmental institutions. Here, models may be valuable auxiliary tools to close information gaps in measurements in space and time. While these models highly simplify the hydrogeologic complexity and may not agree with point measurements to an arbitrary accuracy, bulk mass fluxes and dynamics may be well-reproduced. In this study, an attempt was made to derive a physically consistent groundwater climatology from integrated simulations of the terrestrial hydrologic and energy cycles from groundwater across the land surface into the atmosphere applying the Terrestrial Systems Modeling Platform (TerrSysMP) over continental Europe. In TerrSysMP, groundwater-to-atmosphere (G2A) closure of the coupled water and energy balances results in a physically consistent, dynamic equilibrium of groundwater dynamics with the land surface and atmospheric forcings by honoring two-way, non-linear feedback processes. Following the protocol of the Coordinated Regional Climate Downscaling Experiment (CORDEX), we present simulation results from a validation time period commencing in 1989 spanning almost 30 years. The resulting time series constitute a first terrestrial G2A climatology including groundwater, which can be used to assess future potential trends and anomalies. In addition, we will discuss the limitations of our simulation approach and the challenges of assessing the results utilizing local measurements and regional modeling results from previous studies.

Talk

### Paleoenvironmental and climatic implications of Oligocene–Miocene semi-arid paleosols from Kazakhstan

**Alexandra Hellwig[1,2], Silke Voigt[2], Andreas Mulch[2,3], Konstantin Frisch[2], Axel Gerdes[2], Thomas Voigt[4]**

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Paleosols archive variability in soil temperature, soil $pCO_2$ and the degree of chemical weathering and are hence sensitive to changes in vegetation, rainfall and temperature on seasonal and longer timescales. Mudstones of the 180 m-thick alluvial Alakul and Aidarly Formations in the Kendyrlisai Valley (Ili Basin, SE Kazakhstan) yield a series of calcrete-bearing paleosols which developed during times of landscape stability in a seasonal, semi-arid environment. U-Pb dating of calcrete nodules (Alakul Formation) reveals a late Oligocene–early Miocene age of 23.3±3.4 Ma. Our study presents changes in facies, chemical weathering intensity and paleoenvironment deduced from elemental and stable isotope geochemistry.

Paleosol profiles in the Alakul Formation develop from finely dispersed calcrete patches to consolidated nodules throughout the profile, and thus point to a decreased sedimentation rate during pedogenesis. Calcrete nodules consist almost exclusively of pure calcium carbonate with rare substitution of Ca by Mg, indicating a constant supply of Ca by weathering and solution during calcrete formation. Intra nodule variability suggests more than one weathering and calcrete formation phase with a higher supply of Ca, Mg and Fe during early stages of nodule formation. Weathering ratios (CIA, CPA and Mg/Al) obtained from the co-occurring mudstones suggest moderate weathering intensity mainly represented by feldspar weathering. The presence of Mg-bearing clay minerals indicates evaporative conditions with alkaline waters in the vadose zone, likely sourced by ground water rise into the capillary fringe. Carbon isotope values ($\delta^{13}C$) indicate dominance of $C_3$ vegetation cover under re-occurring moisture stress, resulting in higher $\delta^{13}C$ values and lower respiration rates.The correlation of carbon and oxygen isotope values points towards an increased aridity in the basin with both increased soil water evaporation and water stress on plants.

Combined $\delta^{13}C$ data derived from soil carbonates and organic matter serve for calculations of $pCO_2$values, which requires estimates of additional parameters such as temperature and the $\delta^{13}C$ of the atmosphere. The assessment of the soil-respired $CO_2$concentration, S(z), yields the greatest degree of uncertainty and is calculated by using MAP values derived from the depth to the calcrete-bearing horizon in the paleosol horizons. The application of an S(z) value of 2000 ppm results in $pCO_2$ values of 313±110 ppm for the late Oligocene-early Miocene. The value agrees with the $pCO_2$ compilation by Foster et al. (2017) and supports the hypothesis that the late Oligocene global decrease in $pCO_2$ contributed to aridification in Central Asia.

Talk

## Assessing Groundwater vulnerability to climate change using an index based approach

**Christina Hölbling**[1,2], **Stefan Broda**[1], **Peter Chifflard**[2], **Dorthe Pflanz**[1], **Jörg Reichling**[1]

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An index-based approach is developed to analyze the quantitative vulnerability of groundwater resources to climate change in Germany. The approach is based on nation-wide available information of the type of cavity and aquifer yield, as well as certain climate parameters. The parameters are framed within a classification and weighting scheme. In a first step, the approach was tested by calculating the vulnerability index with mean annual groundwater recharge rates for two reference periods: 1961-1990 (historic) and 1981-2010 (current). The obtained vulnerability index alterations with respect to the historic and current groundwater recharge periods revealed good correspondence with the general trend of groundwater level time series for the given period. In a next step, the approach was applied to calculate the groundwater vulnerability to climate change using climate projections of the RCP 8.5 scenario based on the climate model MOHC-HadGEM2-ES. Monthly and annual groundwater recharge rates for a historical and a future period were calculated according to Döll & Flörke (2005).

Overall, low to medium vulnerabilities were calculated for the German groundwater resources, whereas karst areas such as the Swabian and Franconian Alb indicate a relatively high sensitivity to climatic changes and require adaptation measures. Monthly vulnerability calculations show that, despite the low annual index values, temporary high vulnerabilities are possible at the regional level. The results show a strong dependence of the calculated index values to the weighting of the parameters considered for the index calculation. The obtained results compare well to other studies on the effects of climate change on Germany's groundwater resources.

Talk

## Multipurpose simulations underground dam scenario in order to revitalize the aquifer and optimize the balance in drought conditions

**Alireza Nikbakht Shahbazi**[1], **Hamidreza Majedi**[2], **Fatemeh Hassani**[2]

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Ghaleh-Tal Morghab plain is one of the agricultural poles in Khuzestan province, this plain is in the southwest of Iran and in the Karoon watershed. The negative balance of groundwater resources on the one hand and large quantities of groundwater outlet on the other required the choice of an appropriate artificial nourishment method in the region. The new technology for the construction of underground dams plays an important role in maintaining and optimizing the use of groundwater resources as an economic and executive solution in arid and warm areas. Recently, only superficial feeding options were considered. The construction of dam and pond and wells was carried out, and the result of this project was not successful due to the exaggerated hydrologic calculations. What was considered in this research was the use of an underground dam in order to prevent waste underground water resources which have not the water right from downhill. In this paper, after carefully studying the depth and groundwater maps of the groundwater with the help of existing piezometers and field studies, the status of the rock, the topography and groundwater level, and the study of hydrodynamic conditions suitable for the aquifer, the appropriate site for the construction of the underground dam with the help of modeling and numerical-mathematical method were simulated, the situation was compared before and after the plot. Qualitative and hydrochemical studies were also carried out using aquifer samples. An important indicator during the implementation of this study was geophysical studies and geoelectric studies used to identify the appropriate initial locations in the boundary conditions, the existing structural and hydraulic conditions of the two selected axis options were met. Finally, the The modeling software help is the best offer option and overall dimensions of the dam are determined. In this research, by combining two modeling and geoelectric methods for the first time, the most efficient and most economical method of artificial nutrition design was proposed in terms of geological and hydrological conditions in the Morghab area. How to achieve a positive balance of groundwater table in order to prevent the aquifer from being banned in drought scenarios was predicted.

Talk

## Groundwater in a warming world: the impact of changing climate extremes

**Richard Taylor**

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As the world's largest distributed store of fresh water, groundwater plays a fundamental role in sustaining ecosystems and enabling human adaptation to climate variability and change. The strategic importance of groundwater for global water and food security will intensify under climate change as more frequent and intense climate extremes (droughts and floods) increase variability in precipitation, soil moisture and surface water. Here, the impact of the intensification of the global hydrological system on groundwater replenishment is reviewed drawing upon empirical evidence comprising global satellite data, stable-isotope ratios of O and H tracing water movement across the tropics, and multi-decadal *in situ* piezometric observations across Sub-Saharan Africa. These observations reveal a consistent bias in groundwater recharge to extreme rainfall and provide new insight into recharge pathways that are inconsistent with conventional recharge models used to assess the impacts of climate change. This multi-scale analysis suggests that the intensification of precipitation brought about by global warming not only favours groundwater replenishment in the tropics where this intensification will be most acutely realised, but also increases the vulnerability of groundwater to contamination. Critically, the new insight gained from this analysis informs adaptive strategies such as conjunctive use of surface water and groundwater including 'managed aquifer recharge' associated with extreme precipitation. Overall, the evidence suggest that groundwater has the potential to be a climate-resilient source of freshwater in the tropics, enabling adaptive strategies such as groundwater-fed irrigation and sustaining domestic and industrial water supplies.

# 8b,d) Oceanic oxygen, ice ocean interactions and climate change

**Poster**

## Reconstruction of paleo-redox conditions in particle rain vs. diffusion dominated settings in Pacific Oxygen Minimum Zones

**Sümeyya Eroglu**[1], **Florian Scholz**[1], **Christopher Siebert**[1], **Renato Salvatteci**[2], **Ralph Schneider**[2], **Martin Frank**[1,2]

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The extent and intensity of oxygen miminum zones (OMZs) along productive continental margins are tightly coupled to changes in ocean ventilation and biogeochemical feedbacks. The reconstruction of spatial and temporal changes of these parameters is crucial in order to understand the mechanisms driving marine redox conditions in the past. The application of redox-sensitive proxies like molybdenum (Mo) and its isotopes can unravel valuable information archived in the sedimentary record. However, the mechanisms by which Mo is delivered to and sequestered by sediments in OMZs are still poorly constrained.

Here, we compare Mo concentrations and isotope compositions of short sediment cores (up to 40 cm) as well as paleorecords (several meters) covering the last 10,000 years from the OMZs in the Gulf of California and the Peruvian Margin [1]. The investigated sites differ in sedimentation rate, export production and ocean circulation.

A short sediment core from the Gulf of California OMZ has $\delta^{98}$Mo signatures ranging from +1.64 to +2.13 ‰ and Mo concentrations between 3 and 17 µg $g^{-1}$. The paleorecord from the same location has $\delta^{98}$Mo signatures ranging from +1.66 to +1.92 ‰ and Mo concentrations between 5 and 10 µg $g^{-1}$. In contrast, short sediment cores from the Peruvian OMZ are isotopically lighter (+1.16 to +1.55 ‰) with higher Mo concentrations (11 to 101 µg $g^{-1}$) [1]. Similarly, the corresponding paleorecord reveals a large range in $\delta^{98}$Mo signatures (+1.23 to +1.79 ‰) and Mo concentrations (13 to 98 µg $g^{-1}$). The differences between the two settings can be explained by unique transport mechanisms of Mo to the sediments. The OMZ off Peru is characterized by high organic carbon rain rates and intense water column denitrification. The sedimentary Mo inventory is consequently dominated by particulate supply via Fe-oxides [1] and organic matter. In contrast, the OMZ in the Gulf of California is characterized by a lower organic carbon rain rate and denitrification does not occur in the bottom waters. The Mo flux is dominated by diffusion into the sediments. These findings demonstrate the importance of particulate vs. diffusive Mo delivery in controlling the Mo isotope composition of sediments with important implications for the reconstruction of paleo-redox conditions in the eastern equatorial Pacific.

[1] Scholz et al. (2017) GCA 213, 400-417

**Poster**

## Mn/Ca ratios of Ammonia tepida as a proxy for seasonal hypoxia in coastal ecosystems: the case of Lake Grevelingen, The Netherlands

**Jassin Petersen**[1,2], **Christine Barras**[2], **Antoine Bézos**[2], **Carole La**[2], **Filip J R Meysman**[3,4], **Aurélia Mouret**[2], **Caroline P Slomp**[5], **Frans J Jorissen**[2]

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Hypoxia (oxygen concentration < 63 µmol/L) is a natural phenomenon which due to human activities (i.e., global warming and increased nutrient inputs) is affecting an increasing number of coastal marine environments. Here we have focused on a coastal ecosystem in the Netherlands, Lake Grevelingen, with seasonally hypoxic to anoxic (no measurable oxygen concentration) bottom waters. The benthic foraminifer *Ammonia tepida* was present in these constraining conditions. The geochemical composition of living specimens of *A. tepida* was studied in order to explore the possibility to develop a proxy for seasonal coastal hypoxia. We focused on Mn/Ca ratios because manganese is a redox element which is soluble in reduced form ($Mn^{2+}$), and hence can be incorporated into benthic foraminiferal tests under low oxygen conditions. The study is based on samples of three stations along a depth transect, which have, despite the seasonal variability at each site, contrasting $Mn^{2+}$ concentrations in the pore water of the sediment surface. Moreover, the sediment and pore water geochemistry of Lake Grevelingen shows a dominant influence of microbial activity (i.e., cable bacteria activity) on the $Mn^{2+}$ concentrations in the pore water, a phenomenon which could be indirectly linked to the intensity of coastal hypoxia.

The use of Laser Ablation-ICP-MS (LA-ICP-MS) allowed us to compare Mn/Ca ratios of different parts of the benthic foraminiferal test (i.e., penultimate and antepenultimate chamber, central part of the test) and evaluate their proxy potential. Results show that the higher Mn/Ca ratios at the deepest station compared to both other stations translate a trend of increasing cable bacteria activity with increasing hypoxia to anoxia. The signal preserved in the central part of the benthic foraminiferal tests, which is supposed to reflect the entire calcification history of the analysed specimen, appears to be most suitable to serve as a proxy for hypoxia/anoxia. The Mn/Ca ratios of the latest calcified chambers showed a large variability which is tentatively attributed to active foraminiferal migration in the surficial sediment.

It appears that Mn/Ca ratios of *A. tepida* give insight into the complex spatial and temporal variability of pore water manganese, cable bacteria activity and ultimately hypoxic events in coastal ecosystems.

Talk

## A Southern Ocean perspective on climate, $CO_2$ and ice sheets

**Thomas Ronge**[1], **Jörg Lippold**[2], **Walter Geibert**[1], **Frank Lamy**[1,3], **Gesine Mollenhauer**[1], **Matthias Prange**[3], **Bernhard Schnetger**[4], **Finn Süfke**[2], **Ralf Tiedemann**[1,3]

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Decades ago, the analysis of ancient air – trapped deep inside of Antarctic glaciers – revealed an astonishing pattern of atmospheric $CO_2$. Ever since we've first laid our eyes on these intriguing signals– alternating between glacial lows and interglacial highs – an overall question emerged: *Where was the $CO_2$ stored during the glacials and how was it released back to the atmosphere during deglacial transitions?* In general, several carbon reservoirs like the terrestrial biosphere or permafrost soils might interact with, and drive the atmosphere on these glacial-interglacial timescales. By far the largest influence however, might come from the deep ocean. Today, this reservoir stores up to 60-times the carbon, of which is stored in the entire atmosphere. Hence, tiny changes in the oceanic C-cycle might have severe ramifications for atmospheric $CO_2$-levels. Parallel to global $CO_{2\ atm}$, Antarctic temperatures rose, while the expanded ice shelves suffered from a massive deglacial collapse.

The timing and succession of events pointed to the climatic role of the Southern Hemisphere in general and the Southern Ocean in particular and raised a second question: *What was the physical process, which connected these deglacial events?*

Until today, the international community compiled numerous studies from terrestrial and marine (distal and proximal) archives to shed light onto this dynamic system. These studies revealed a closely connected system between Antarctic sea ice and ice shelves, deep-water and atmospheric circulation, oceanic stratification, the biological pump and also bipolar teleconnections. Here, we want to discuss the current scientific knowledge and present new isotopic data – measured on planktic and benthic foraminifers as well as bulk sediments – that show how Southern Ocean overturning circulation changed on glacial-interglacial timescales and influenced the residence times of circumpolar deep-waters as well as their transport onto the continental shelf regions. In combination with other parameters, the deglacial increase in Southern Ocean overturning represents a plausible link that might explain the parallel evolution of several deglacial climate parameters.

Talk

## Reconstructing oxygen minimum zone-type biogeochemical cycling in the geological record

**Florian Scholz**[1], **Sebastian Beil**[2], **Klaus Wallmann**[1], **Moritz F. Lehmann**[3], **Sascha Flögel**[1], **Ann Holbourn**[2], **Wolfgang Kuhnt**[2]

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Because of anthropogenic global warming, the world ocean is currently losing oxygen. This trend called ocean deoxygenation is particularly pronounced in upwelling-related oxygen minimum zones at low latitudes. In these high productivity areas, the temperature-related oxygen drawdown is additionally modulated by biogeochemical feedback mechanisms: the release of iron and phosphorus from anoxic sediments supports primary production and respiratory oxygen consumption in a positive feedback loop. In contrast, the loss of fixed nitrogen through denitrification and anaerobic ammonia oxidation (anammox) in the anoxic water column imposes a negative feedback on primary productivity and oxygen consumption. Similar feedbacks were likely active during past periods of global warming and ocean deoxygenation. However, their integrated role in amplifying or mitigating climate change-driven ocean anoxia has not been evaluated in a systematic fashion. Moreover, many studies on past deoxygenation events emphasize anoxic-sulfidic (i.e., euxinic) basins rather than upwelling-related oxygen minimum zones as modern analogue systems.

Here we propose a suite of paleo-proxies for iron, phosphorus and nitrogen cycling, which can be used to identify oxygen minimum zone-type biogeochemical cycling in sedimentary paleo-archives. These proxies are applied in two open-marine upwelling systems in Earth history: the late Quaternary oxygen minimum zone off the coast of Peru and the Cretaceous Tarfaya Basin in the Proto-North Atlantic. Based on data from these two systems, we discuss evidence for feedbacks between sedimentary iron and phosphorus release, water column nutrient cycling and redox-conditions on glacial-interglacial timescales and in the context of the Cenomanian-Turonian Oceanic Anoxic Event 2.

Talk

## Antarctic Ice Sheet Dynamics Coupled to Global Climate Events

**Michael E Weber[1], Christopher J Fogwill[2], Matthew DeCesare[3], Nicholas R Golledge[4], Natalya Gomez[5], Peter U Clark[6]**

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Knowledge on the response of the Antarctic Ice Sheet (AIS) to deglacial changes is very limited because most shallow marine and terrestrial sediment sequences cannot be dated adequately, reveal only the latest, post-sea level rise, ice retreat, or resolve only local responses, leaving much room for speculation on the true dynamics and the AIS contribution to past global sea-level rise.

The record of iceberg-rafted debris in deep-ocean sediment from Iceberg Alley provides a nearly continuous history of eight AIS discharge events (AID) during deglaciation (Weber et al., 2014, Nature), each lasting for centuries. Accordingly, major AIS mass loss brackets Meltwater Pulse 1A (AID6) and 1B (AID2), between ~14.7 – 11.3 ka. Even throughout the Holocene repeated decadal-to-centennial scale, smaller fluctuation in AIS mass volume document far-reaching effects (Bakker et al., 2016, Nature).

Independent confirmation comes from analysis of the Patriot Hills blue ice area, indicating at least 650 m of AIS elevation draw down across the Weddell Sea Embayment during the Antarctic Cold Reversal (ACR, 14.7 – 12.7 ka) (Fogwill et al., 2017, NatSciRpts). Foraminiferal radiocarbon ages from shallow-marine sediment archives in the eastern Ross Sea (DeCesare et al., pers. com.) directly constrain grounding line retreat of the West AIS at 14.7 ka (30 km) and 11.5 ka (200 km), likely contributing to AID6 and AID2, respectively. These ages also constrain ice shelf collapse approximately the size of Larsen-B occurred 12.3 ka, likely contributing to AID3.

Close agreement between these different geological and ice-core records and thermodynamic ice-sheet modelling driven by deglacial ocean temperature changes simulated in an intermediate complexity climate model, confirm that the AIS was highly-dynamic during the last glacial termination (Golledge et al., 2014, NatCom), in sync with global climate events, and likely driven by ocean thermal forcing. A dynamic ice sheet model coupled to a global sea level model (Gomez et al., 2013, EPSL) suggests that the ice discharge in Antarctica may have also responded to short timescale sea level variations associated with Northern Hemisphere ice cover changes through the deglaciation.

All these recent findings are in marked contrast to previous scenarios of minor and late deglacial dynamics, and argue for a much more dynamic deglacial AIS (see review article of Noble et al, submitted to RoG), which is important in light of current discussions on potential AIS collapse in the near future and its impact on sea-level rise for the coming decades to centuries.

Talk

## The record of the Mid Barremian event in the Boreal Realm (Early Cretaceous)

**Lena Wulff[1], Jörg Mutterlose[1], André Bornemann[2]**

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The Cretaceous interval, the warmest period in the Mesozoic was characterized by warm, humid greenhouse conditions. Several geologically short termed climatic perturbations lead to so called oceanic anoxic events (OAE's), documented in the marine sedimentary record. During these events, ocean bottom waters were depleted in oxygen, causing the widespread deposition of black shales. OAE's, particularly the T-OAE (Toarcian; Jurassic), the OAE 1a (Aptian; Early Cretaceous) and the OAE 2 (Cenomanian; Late Cretaceous) have been intensively studied for more than 50 years.

Apart from these well-known OAE's, black shales of mid Barremian age are currently discussed as a potential additional OAE. Particularly mid Barremian black shales from the Boreal Realm (northern Germany), which have been well documented in the past, possibly reflect this OAE. However, current models suggest that the anoxic bottom water conditions, which caused these black shales, were temperature controlled and reflect a regional signal. On the other hand, mid Barremian black shales have been recognized in the Tethys (Switzerland, Italy, France,) indicating rather a global distribution of this event.

In order to understand whether these Barremian black shales reflect a typical OAE signal, a core recently drilled in northwest Germany has been studied in detail for calcareous nannofossil biostratigraphy and biometry as well as stable isotopes.

Poster

## Climatic links between the subarctic and subtropical North Atlantic during the last interglacial (MIS 5e)

**Anastasia Zhuravleva**[1], **Henning Bauch**[2]

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Model simulations and proxy data from the North Atlantic reveal a high-to-low latitude teleconnection that affects the subtropical ocean circulation via ocean-atmospheric forcing. While this climatic coupling is well-studied for the last glaciation and Termination 1, it has never been investigated for the last interglacial (MIS 5e, ~129-116 ka) with sufficient resolution. Here, we close this gap by comparing records from the subarctic deep-water formation sites with new assemblage and stable isotope data from the Bahama region, an area influenced by seasonal shifts of the Intertropical Convergence Zone (ITCZ).

Our proxy records from the various oceanic basins reveal for early MIS 5e a comparable millennial-scale Younger Dryas-like cooling event (~127 ka), which can be used as an important marker allowing for a better chronostratigraphic constraint of the MIS 5e interval. In the subtropical North Atlantic, the abrupt cooling could not be reconciled with insolation forcing but is associated with a sudden southward shift of the ITCZ, the latter being linked to a short-term freshwater-related reduction in strength of the ocean overturning. These results help to disentangle the roles of different mechanisms controlling low-latitude climate across MIS 5e (insolation versus oceanic and/or atmospheric versus freshwater forcing). It leads to the conclusion that a persistent high-latitude freshening and unstable deep-water overturning during early MIS 5e accounted for a “transitional” and, therefore, particularly vulnerable climatic regime during this time period, causing the cold-warm switches akin to those observed during the last glacial termination.

# 8c) Loess systems and the reconstruction of Pleistocene climate dynamics

Talk

## Extra-long interglacial in Northern Hemisphere during MISs 15-13 and its influence on the second major dispersal of African hominins

**Qingzhen Hao**[1], **Luo Wang**[1], **Frank Oldfield**[2], **Zhengtang Guo**[1]

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In the MIS sequence, MIS 14 (563−533 kyr BP) stands out as a short and mild glacial epoch in many records of the last 700kyr. Confirming the extent of Northern Hemisphere (NH) ice sheets during MIS 14 can provide new insight into the 100-kyr climate cycles and improve our understanding of the forcing mechanism of the Pleistocene glacial and interglacial cycles.

Here, based on the demonstrable link between changes in Chinese loess grain-size and NH ice-sheet extent, we use loess grain-size records to confirm that northern ice-sheets were restricted during MIS 14. This is in accordance with the marine and continental records in the NH. Thus, an unusually long NH interglacial climate of over 100 kyr persisted during MISs 15−13, much longer than expected from marine oxygen isotope records. However, the evidence from many middle-high latitude records from the Southern Hemisphere suggests typical glacial-like climate conditions in middle-high southern latitudes, and we tentatively attribute the cooing of MIS 14 as indicated by the marine $\delta^{18}O$ record to South Pole processes.

The extra-long and warm, predominantly interglacial style climate in the Northern Hemisphere during MISs 15−13 may have had a profound influence on the migration of early humans within the context of alternating glacial and interglacial climates. The evidence from genetic analysis and archaeological investigations suggest that hominins of African origin dispersed, and similar forms of hominins and Acheulean bifacial handaxes occurred in regions on both sides of the Mediterranean about 600 kyrs ago. Therefore, we propose that the extra-long duration of interglacial/mild stadial climates during MIS 15−13 may have provided favorable conditions over 100 kyr for the second major dispersal of African hominins into the Eurasia region during the middle Pleistocene.

Talk

## Aeolian activity changes during OIS 2 in Central Europe and its influences on the Late Glacial human expansion into the North

**Olaf Jöris**[1,2,3,4], **Peter Fischer**[5], **Sonja B. Grimm**[6], **Martin Street**[2], **Bernhard Weninger**[7]

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The geographic distribution of humans largely depends on both the demographic history of populations and the climatic and ecological settings of the regions populated. In global perspective, it seems that humans had not overcome some climatic constraints before the end of the Last Glacial Maximum (LGM) ~25–20 ka and the beginning of the Late Glacial warming period ~14,750–12,650 years ago, when hunter-gatherer groups in different parts of the Old World expanded from their glacial refuge areas into previously un-populated regions, culminating in the conquest of the Americas at an unprecedentedly rapid speed. With the increasing availability of long time-series of a variety of palaeoclimate proxies, over the last three decades archaeologists and population modellers worldwide have been aiming at an improved understanding of the climatic influences on the dispersal and demography of past human populations, by linking the archaeological record with the records of different climate proxies. In most such studies, Late Glacial hunter-gatherers were considered to have more or less directly – and passively – reacted to the rapidly changing temperatures during this interval. As a result, temperature changes were considered the basic trigger underlying environmental change, having thus been of utmost influence on past human dispersal. Here, we integrate selected high-resolution palaeoenvironmental data with a comprehensive European-wide archaeological data base of radiometric age-determinations, documenting that the post-LGM re-occupation of Central Europe was controlled to a larger degree by aeolian sediment loads rather than by any direct influence of temperature changes.

Key-words: Archaeological data bases, radiocarbon dating, calibration, loess accumulation.

Talk

## Semlac – a key loess-palaeosol sequence of the Banat Lowland (Western Romania) and a prominent Pleistocene section for the SE-Carpathian Basin

**Holger Kels**[1], **Philipp Schulte**[1], **Christian Zeeden**[2], **Ulrich Hambach**[3], **Nicole Klasen**[4], **Frank Lehmkuhl**[1]

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The Carpathian Basin (CB, Pannonian Basin, Middle Danube Basin) is an important area for studies on loess records on European- and Eurasian scale. Reinvestigations of the Semlac loess section, situated in the South-eastern CB and located at an undercut slope position on the right bank of the Mureş River in its lower reaches (Banat region, western Romanian), show that this site serves as a key-section connecting rather thin sections of loess-like sediments of the Banat foothills close to the Carpathian Mountains with well-studied thick loess sections of the central CB in Hungary and Serbia.

The more than 10 m thick loess sequence includes four fossil soil-complexes developed in homogenous and relatively fine silty loess, dating back to marine isotope stage 10. Therefore, Semlac is regarded as a prominent section for the CB, offering possibilities to a) improve the understanding of the type and composition of the lowland loess sequences in the CB (loess homogeneity and pedogenic alteration) also beyond the last interglacial palaeosol complex, b) reconstruct the temporal setting of several short loess-palaeosol successions in the region, c) gain better insight into the regional palaeoenvironments of the last 300 ka and d) compare the loess of the region to loess-sequences in adjacent areas and even to dust proxy data of the northern hemisphere. The integrated age model is based on luminescence dating in its younger part. The age model of the older part is based on correlation of palaeopedologic, environmental magnetic, and sedimentological data to independently dated northern hemispheric palaeoenvironmental proxy records. This allows comparisons to data from loess sections of the region (Hungary and Serbia) and even from the wider northern hemisphere.

The research is part of systematic reinvestigations in the frame of the German CRC 806-project (Collaborative Research Centre 806), focussing on a better understanding of the dispersal of the first Anatomically Modern Humans (AMH) into Europe and its palaeoenvironmental context. Although no archaeological remains have been found at the site of Semlac until now, this section provides important local palaeoenvironmental data supporting a better understanding of the archaeologically rich but temporally less resolved sites in the closer vicinity especially those at the Banat foothills of the Carpathian Mountains.

Talk

## Is there a need for readjustments concerning Late Pleistocene paleoenvironmental dynamics in the northern loess distribution zone of Bavaria (Germany)?

**Lydia Krauß**[1,3], **Nicole Klasen**[2], **Philipp Schulte**[1], **Frank Lehmkuhl**[1]

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Loess-paleosol-sequences (LPS) represent some of the most complete records of local-scale paleoenvironmental dynamics in terrestrial environments. The Attenfeld sequence is located around 4 km north of the Danube River and within the southern extent of the Franconian Jura in Bavaria (Germany). The Danube is believed to be one of the main sediment sources of LPS in Southern Germany and further east. However, studies on LPS in this area lack actuality. Therefore, a multi-proxy approach has been applied (analyses of grain-size distribution, element composition, and sediment color attributes). Additionally, two samples were taken for dating with optically stimulated luminescence (OSL). Results show that all preserved units experienced reworking, which might be due to generally higher precipitation amounts and a larger slope angle when compared to other LPS. Unexpected luminescence age estimates are raising further questions…

Talk

## Loess-paleosol sequences in northern Iran – Highly resolved archives of paleoenvironmental change during the Middle- and Upper Pleistocene

**Tobias Lauer**[1], **Stefan Vlaminck**[2], **Martin Kehl**[3], **Manfred Frechen**[4], **Christian Rolf**[4], **Eva Lehndorff**[5], **Jafar Sharifigarmdare**[6], **Ali Shahriari**[7], **Farhad Khormali**[6]

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On the northern foothills of the Alborz Mountains and in the so-called Iranian Loess Plateau thick Quaternary loess-paleosol sequences (LPSS) are preserved hosting important information about environmental changes in the Southern Caspian Lowlands and adjacent areas[1]. The region is characterised by a hydroclimatic gradient with decreasing precipitation from the west to the east and from the south to the north. Hence, there LPSS can be studied over short distance that likely formed synchronously and under presumably different climatic conditions. This presentation gives an overview on the research conducted within the DFG-founded project “Loess in northern Iran and its palaeoclimatic implications”.

Besides OSL dating [2,3], micromorphological studies [4], bulk mineralogical and geochemical research [5], as well as rock and palaeomagnetic investigations have been performed on various loess sections.

Results mainly from the last few years are summarized and the high potential of Iranian loess to better understand the triggering factors for periods of increased dust accumulation, soil formation and changes in dust provenance are outlined.

The presentation shows that especially for the last glacial- interglacial cycle, the loess-paleosol sequences are very valuable archives to reconstruct shifts in temperature- and precipitation and its influence on landscape evolution/ soil formation. At the profile Toshan, it is for instance illustrated that the last interglacial soil was formed under reduced or absent dust deposition on penultimate glacial loess (postsedimentary). Soil-formation during the Pleniglacial happened under ongoing dust deposition (synsedimentary) in response to short-lived and relatively moist interstadials[5].

**Key words**: Iran, loess, palaeoclimate

1. Kehl, M. Quaternary loesses, loess-like sediments, soils and climate change in Iran. *Reli. Boden, Paläoklima* **24,** (2010).

2. Lauer, T. *et al.* Luminescence-chronology of the loess palaeosol sequence Toshan, Northern Iran – A highly resolved climate archive for the last glacial–interglacial cycle. *Quat. Int.* **429,** 3–12 (2017).

3. Lauer, T. *et al.* The Agh Band loess-palaeosol sequence – A terrestrial archive for climatic shifts during the last and penultimate glacial–interglacial cycles in a semiarid region in northern Iran. *Quat. Int.* **429,** 13–30 (2017).

4. Vlaminck, S. *et al.* Loess-soil sequence at Toshan (Northern Iran): Insights into late Pleistocene climate change. *Quat. Int.* **399,** 122–135 (2016).

5. Vlaminck, S. *et al.* Late Pleistocene dust dynamics and pedogenesis in Southern Eurasia – Detailed insights from the loess profile Toshan (NE Iran). *Quat. Sci. Rev.* **180,** 75–95 (2018).

Talk

## Desert Margin Loess in Southern Tunisia

**Sascha Meszner[1], Moncef Bouaziz[3], Ulrich Hambach[2], Alexander Fülling[5], Georg Mettig[1], Maximillian Pachtman[1], Manuel Recio Espejo[4], Dominik Faust[1]**

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Eolian deposits cover huge areas in the surroundings of the village of Matmata in southern Tunisia. Especially valley and depression floors are covered by an up to 30 m think layer of silty and very fine sandy material. We are investigating more than 11 loess-paleosol sequences in order to build up a solid stratigraphy of loess units for this region.

The deposits show a clear internal stratigraphy between loess units and intercalated paleosols. We suppose this as a result of alternating arid and more humid climate conditions. Therefore, the loess-paleosol sequences of Matmata are very suitable to reconstruct the past environmental conditions at the northern margin of the Sahara desert.

The intercalated paleosols show several features suggesting an autochthonous formation. For example, the upper horizons are decalcified however reddish, whereas lower parts show a strong carbonate enrichment. Additionally, the environmental magnetic properties indicate an autochthonous soil formation as well.

Our chronostratigrphy frame will be based on several OSL age estimations and first results are already available.

Talk

## A critical re-evaluation of palaeoclimate proxy records from loess sections in the Carpathian Basin

**Igor Obreht[1], Christian Zeeden[2], Ulrich Hambach[3], Daniel Veres[4], Slobodan B. Marković[5], Frank Lehmkuhl[6]**

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In the Carpathian Basin, loess is the most important archive for inferring Quaternary palaeoclimate variability. Palaeoclimate inferences based on magnetic susceptibility and grain-size distribution, as the most commonly used palaeoenvironmental proxies for the Carpathian Basin loess indicate colder and drier climatic conditions during glacials compared to interglacials with soil development under warmer and more humid climate. However, with an increasing number of studies using novel proxies in loess research, such a traditional understanding of dry and cold glacials and humid and warm interglacials in the Carpathian Basin has been questioned. For example, mollusc based climate reconstructions suggest generally warm and very dry glacial summer conditions with mean July temperatures up to 21˚C for the southern Carpathian Basin. Results based on stable carbon isotopes strongly oppose such high summer temperatures, but studies based on n-alkanes are in general agreement with the mollusc data when it comes to the vegetation reconstruction indicating mostly steppic conditions. However, n-alkane studies contradict warm and dry glacial conditions as indicated by mollusc-based reconstructions, pointing instead to cold and relatively humid glacials. Consequently, the current stage of the art of the palaeoclimate reconstructions from loess in the Carpathian Basin is rather inconsistent.

In order to obtain a better understanding of the existing palaeoclimate data from the Carpathian Basin loess, we have re-evaluated and re-interpreted the available data. We discuss and propose a coherent interpretation of rock magnetic, grain-size, malacological, stable carbon and nitrogen isotope, n-alkane and bacterial membrane lipid data for the last glacial cycle loess in the Carpathian Basin. We can show that glacial conditions in the Carpathian Basin led to a notable increasing North-South gradient in temperature and an even stronger expressed decreasing trend in humidity, and that most of the biomarker proxy data conducted in loess for the very dry southern part of the Carpathian Basin show a strong bias towards arid conditions. Glacial conditions were drier and colder than previously proposed, but notably warmer than in other parts of Western, Central, and Eastern Europe. The vegetation cover was mainly characteristic of steppic environments during both glacials and interglacials.

Talk

## High resolution luminescence dating of the Titel loess core (Serbia, Eastern Europe) over the last two glacial-interglacial cycles

**Zoran M. Peric[1], Jan-Pieter Buylaert[2], Thomas Stevens[3], Slobodan B. Marković[4], Ulrich Hambach[5], Peter Fischer[6], Christian Zeeden[7], Mayank Jain[8], Andreas Vött[6]**

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Aeolian sediments represent ideal materials for the application of luminescence dating methods due to their mineralogical composition showing high amounts of quartz and feldspars. These minerals possess a whole range of luminescence characteristics that make them suitable for luminescence dating. In the case of aeolian transported dust forming loess deposits, it can be assumed that individual mineral grains were completely exposed to sunlight and were sufficiently bleached prior to deposition.

The investigated core near the section Veliki surduk (45°17-18'N and 20°12-15'E) on the Titel loess plateau was chosen for dating, as it shows high rates of sedimentation and no apparent hiatuses which makes this loess-palaeosol-sequence one of the most detailed palaeoclimatic archives of the last two glacial-interglacial cycles in Eastern Europe.

In order to obtain detailed stratigraphic, climatic and chronological information from the Titel loess plateau, a core was drilled to a depth of 23 m in the northern area of the plateau, which provided 99 samples for luminescence dating. The results of this study represent the most detailed luminescence-based age model in Eastern European loess to date.

Using the classic SAR protocol for dating, it has been found that the quartz grains from the Titel loess plateau are precise dosimeters up to ~120 Gy, followed by an apparent saturation of the signal. The highest established dose of feldspars measured by the modified SAR post-IRIR$^{200,290}$ protocol was 854.0±24 Gy. In this way, it has been proven that in the mentioned time range, OSL dating of coarse grain quartz yields reliable age estimates up to 35.8±3.7 ka while the feldspar grains yield ages up to 238±13 ka. Thus, quartz ages allow for reliable dating of MIS 2 deposits while feldspar ages shows better correspondence for the older sections up to MIS 7.

The post-IRIR$^{200,290}$ protocol did not determine the saturation of feldspar minerals, which has largely raised the age limit for luminescence dating at the Veliki surduk section, and most probably, also on other loess profiles in Serbia. The application of various protocols and measurements applied to different groups of minerals and their fractions give these research a far-reaching methodological significance.

Poster

## Loess-paleosol sequences in north-eastern Serbia: a link between the Carpathian Basin and the Balkan paleoenvironment

**Zoran M. Perić[1], Slobodan B. Marković[2], Milivoj B. Gavrilov[2], Miloš Ranković[2], Yunus Baykal[3], Philipp Schulte[4], Ulrich Hambach[5], Frank Lehmkuhl[4]**

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On the territory of Serbia, Pleistocene aeolian deposits are mainly distributed in the Vojvodina region where they cover large areas only separated by the alluvial plains and terraces of the Danube and Tisza rivers. Unlike the loess sequences in the Vojvodina, in north-eastern Serbia the loess formations are quite discontinuous. In this region we mainly find smaller, isolated loess blankets lying over older slopes and river terraces.

Here we present first results from a typical loess site of this region located in the vicinity of the village of Kisiljevo. The investigated loess-paleosol sequence is exposed in the eastern part of the village (44.737548´ N, 21.404791´ E). In the current stage of this study, it was possible to conduct a detailed description of the profile, color determination of the sediment and the determination of initial low field magnetic susceptibility

The Kisiljevo loess sequence is fairly simple in its composition. The profile exposes a round 11 m thick series of loess and is interspersed with weakly developed paleosols. The profile displays a generally uniform coloration, varying from pale yellow, light yellowish brown to light olive brown loess.

On a depth of about 7 meters, the loess is intercalated with a distinctive layer of approximately 50 cm thickness. This layer is densely intersected with insect channels and cavities of recent age and shows all features of volcanic ash. The most likely candidate for the origin of this potential tephra layer is the Campanian Ignimbrite (CI) super-eruption of the Phlegraean Fields (Italy) dated to 39-40 ka. The presence of CI tephra on this site would suggest a more western and northern distribution of the Campanian Ignimbrite eruption ash than stated in previous studies (e.g. Fitzsimmons et al., 2013; Smith et al., 2016; Veres et al., 2013). Nevertheless, it coincides with the finding of the CI ash at the eastern end of the Danube Iron Gates (Lowe et al., 2012) and thus, providing so far a minimum northern extend of the CI-tephra dispersal in the Carpathian Basin.

The geographical location of the Kisiljevo loess profile presents a unique opportunity to reconstruct the paleoclimatic and paleoenvironmental conditions in the transitional region between north-east Serbia and the Carpathian basin at the western end of the Iron Gates. The expected results of this study will contribute to the better understanding of the connections between the paleoclimatic and paleoenvironmental conditions of the Carpathian Basin and the Balkan region.

**Talk**

## Atmospheric dust as a climatic proxy in Late Paleozoic of Iran

**Mehrdad Sardar Abadi**, **Gerilyn S. Soreghan**

*The University of Oklahoma, United States of America*

The Late Paleozoic was earth's longest Phanerozoic glaciation, with ice sheets ultimately covering large parts of the Gondwanan continent, to latitudes as low as 32°S during peak icehouse conditions. Here we focus on the dust record of strata of the Central Persian Terrane (CPT) that accumulated during the Middle Pennsylvanian to earliest Permian acme of the Late Paleozoic Ice Age (LPIA). The CPT was located along the northern Gondwanan margin, within the Paleo-Tethyan ocean at ~30$^{o}$ S, and records deposition consisting of a cyclic succession of warm-water, shallow-marine carbonates throughout Late Pennsylvanian – earliest Permian time. The extensive carbonates across the CPT during the Late Paleozoic indicate the presence of broad carbonate platform isolated from siliciclastic influx, except that delivered by eolian influx. In order to reconstruct a record of eolian flux in the CPT, we combine sedimentologic measurements with geochemical proxies to reconstruct atmospheric dust concentrations through the study intervals, and assess the magnitude, source(s), and possible forcing(s) of the dust variations.

The non-authigenic silicate fractions extracted from these carbonates record atmospheric dust and comprise quartz, clay, trace feldspar and heavy minerals. The weight % dust within the carbonate cycles of the studied interval varies from 0.04% to 10.14%. However, the dust content exhibits peaks generally occurring at cycle boundaries, where weight %ages vary from 10.84% to 80.80%, and covary positively with values of detrital (dust) proxies (Ti, Sr, K, Al, Zr) and magnetic susceptibility (χin). Trends in grain-size distributions of the dust component through the studied interval covary with trends in with dust content (weight percent). Most dust samples exhibit modal grain sizes (volume-based) between 1–15 µm through the Moscovian interval and 10–75 µm through the Asselian interval. Number distribution of the dust particle sizes exhibits cyclic patterns, however, there is no evident temporal trend through the studied intervals.

Variation in the dust content through the studied sections provides an indicator of temporal change in atmospheric loading that varied at both glacial–interglacial and higher–frequency (<$10^4$ yr) scales. Quantitative cyclostratigraphic analyses suggest these variations relate to waxing and waning of the southern hemisphere ice sheets controlled by Milankovitch-scale cyclicity. The stratigraphic pattern of the amount of dust (wt%) through the studied intervals indicates minimal dust flux during highstand times, and peak dust amounts coinciding with glacial lowstands. Larger modal size distributions at or near the cycle boundaries affirm a 2 – 4 fold increase in dust deposition during incipient glaciation to full glaciation phases. However, number distribution of dust particles displays low variability through the intervals, indicating consistency in the majority of dust particles size independent of the amount (and source) of the dust deposited.

**Talk**

## Central European aridity changes in response to North Atlantic SST change during MIS3 (60.000 – 27.000 BP)

**Frank Sirocko**

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The dust content in several sediment cores from Eifel maar lakes reveals the identical succession of cold MIS3 stadials as known from the North Atlantic and Greenland temperature time series. Each cold stadial of MIS3 was characterized by dust activity, which was inactive during the interstadial phases. This patterns indicates a primary influence from the North Atlantic SST on the central European weather and general aridity/humidity changes during the entire MIS3. Dust, pollen and botanical macroremains in the maar lake sediments are used to reconstruct the climate and environment of the Eifel during MIS3. The summer insolation maximum of the early MIS3 is marked by a spruce forest with abundant thermophilous trees, but absence of any dust. The subsequent time from 49 000 – 27 000 BP is marked by stepwise changes of the landscape from the early MIS3 spruce forest to a boreal forest with few dust events, steppe with large dust storms every few years, tundra (with annual dust) and polar desert, which is characterized by absence of all vegetation but reveals annual dust storms after 23 000 BP.

**Talk**

## Fifty shades of loess – potentials and limits of color measurements on loess-paleosol sequences

**Tobias Sprafke**[1], **Simon Meyer-Heintze**[2], **Marcin Krawczyk**[3], **Christian Schäfer**[2], **Robert Peticzka**[4], **Birgit Terhorst**[2]

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Loess-paleosol sequences (LPS) are complex terrestrial archives of Quaternary paleoenvironments formed by the interplay of aeolian sedimentation, pedogenesis, colluviation, and erosion. Units with deviations from typical pale yellowish loess color reflect horizons affected by weathering and pedogenic processes, e.g. decalcification (slightly darker) and carbonate illuviation (lighter), humification (darker), oxidation (more brown / red) and reduction (more pale / grey-blue). Spectrophotometers provide inexpensive, objective, quantitative data of down-profile color variations and allow for a large throughput of samples. High-resolution color data of LPS are increasingly recognized as valuable tools to identify past environmental variations. In this contribution, the potentials and pitfalls of this approach are reviewed and evaluated based on data from loess profiles in Austria, Germany, Poland, and Kazakhstan.

To date standardized measurement devices, protocols and interlaboratory comparisons are lacking. Among the various color spaces and their variables, the CIELAB color space, with the coordinates L* (dark vs. light), a* (red vs. green), and b* (yellow vs. blue) is the most popular and further seems to be most useful to detect various directions of pedogenetically induced color variations. The Redness Index or comparable ratios to quantify the degree of oxidation are in many cases of limited use for paleoenvironmental reconstructions. Color changes by the admixture of colluvial material cannot be separated from those related to in-situ processes and require further proxies, e.g. based on granulometry. Color variations as a tool to classify LPS units using internationally standardized pedological designations is an important step forward to a universal approach to consistently describe loess profiles in a standardized way (Sprafke 2016).

Reference:

Sprafke, T. (2016): Löss in Niederösterreich - Archiv quartärer Klima- und Landschaftsveränderungen. Würzburg University Press, Würzburg, 272 pp.

**Talk**

## Paleoclimatic and tephrostratigraphic potential of last glacial cycle south-eastern European loess-paleosol sequences

**Daniel Veres**[1], **Ulrich Hambach**[2], **Igor Obreht**[3], **Christian Zeeden**[4], **Alida Timar-Gabor**[5], **Janina Bösken**[6], **Lehmkuhl Frank**[6], **Marković Slobodan B.**[7]

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Owing to the nature of their formation, loess-paleosol sequences are valuable in investigating past variability in long-term global dust dynamics. As the primary constituent of loess, mineral dust, a major component of global climate forcing and a proxy that, allows for direct comparison of loess data with chronologically better resolved ice and marine records. Motivated by the recent emergence of high-resolution data on Lower Danube loess-paleosol profiles covering the last glacial cycle, including secure identification of millennial-scale past climate variability, we explore possibilities and drawbacks in comparing regional paleoenvironmental response to millennial-scale climate variability for the last glacial cycle by comparing loess records with better established lacustrine and marine records from south-eastern Europe. We also discuss regional implications in defining an improved loess chronostratigraphic framework based on several lines of chronological evidence, including tephrochronology. As reliable chronological control is still the major limiting factor in exploring the full paleoclimate potential of loess, we discuss several tephra layers that would allow for isochronous tie-points with marine and lacustrine records and in validating the luminescence-based chronologies of loess records. For example, the Campanian Ignimbrite/Y-5 tephra forms the main chronologic/stratigraphic marker in western Eurasia for MIS 3 deposits. As the product of one of the largest Late Pleistocene explosive events in the Mediterranean region dated to 39-40 ka BP, it provides an independent basis for establishing age-depth relationships for the embedding deposits and for comparing records on a wider scale. Following its widespread occurrence in the Lower Danube loess records, we conducted a detailed chronostratigraphic survey of selected sites corroborated by the dating through (mainly) luminescence methods. The aim was to test for the reliability of the luminescence methods in that narrow age-range around 40 ka BP. We show that in general the luminescence age estimates would confirm that the volcanic ash occurrences represent a regionally synchronous depositional event, around 40 ka in age, as suggested by the detailed glass-shard chemical data, albeit significant differences have also been obtained.

Talk

## Stable carbon isotope composition of inorganic carbonates in loess: A tool to differentiate between lithogenic calcareous dust input and pedogenic carbonates in Loess-Palaeosol-Sequences

**Mathias Vinnepand**[1], **Barry Thornton**[2], **Peter Fischer**[1], **Andreas Vött**[1], **Kathryn Fitzsimmons**[3], **Charlotte Prud'homme**[3]

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Loess-Palaeosol-Sequences locally contain high proportions of lithogenic (primary) carbonates (LC) originating from physically weathered rocks within the source area. These LC typically have δ$^{13}$C values close to 0 ‰ (e.g. West et al., 1988). Depending on prevailing climate conditions (in particular precipitation), water percolation dynamics and sediment properties (pH, amount of dissolved inorganic carbon through $_{p}CO_2$) LC are subject to dissolution. The resulting dissolved ions are transported with soil water and precipitate as pedogenic (secondary) carbonates (PC) when the soil solution is supersaturated, in particular close to roots, in response to increasing evapotranspiration or decreasing $pCO_2$.

Strongly decreasing $pCO_2$ towards the surface additionally governs the spatial distribution of PC and restricts the upward migration of ions, despite percolation of water being multidirectional.

During PC precipitation, the stable carbon isotopic composition of soil $CO_2$ and diffusional effects determine the overall δ$^{13}$C values of the PC, which are about by 15 ‰ higher than those of the associated organic matter (Cerling & Quade, 1993). Since the isotopic compositions of LC and PC differ in a predictable way, phases characterised by relatively unaltered dust input can be discriminated from those of PC formation.

Here we use stable carbon isotope compositions to differentiate between LC and PC at high resolution for the last glacial cycle based on the Loess-Palaeosol-Sequence at Schwalbenberg in the Middle Rhine valley in western Central Europe. Based on measurements of bulk carbon and organic carbon contents and their stable isotopic composition, we applied a mass balance equation to calculate the inorganic carbon content and δ$^{13}$C values. Subsequently, PC and LC contributions were estimated using an end member modelling approach.

Our results are in good agreement with pedo- and lithostratigraphy. XRF-derived calcium and calculated inorganic carbon contents facilitate the correction of Ca-based element ratios for subsoil liming effects. Silicate-bond calcium contributions can be identified. Differentiating carbonate types within Loess-Palaeosol-Sequences will enable a better understanding of weathering and soil formation processes under various climatic conditions. This approach may also contribute to elucidate the role of terrestrial inorganic carbon in the global carbon cycle.

Cerling, T.E., Quade, J. (1993): Stable Carbon and Oxygen Isotopes in Soil Carbonates. In: Lohmann, K.C., McKenzie, J., Savin, S., Swart, P.K. (Editors): Climate Change in Continental Isotopic Records. American Geophysical Union.

West, L.T., Drees, L.R., Wilding, L.P. and Rabenhorst, M.C. (1988): Differentiation of Pedogenic and Lithogenic Carbonate Forms in Texas. In: Geoderma 43: 271-287.

Talk

## Stratigraphic interpretations of loess-paleosol sequences and their relevance for land-sea correlations

**Christian Zeeden**[1,2], **Ulrich Hambach**[3,4], **Igor Obreht**[2,5], **Qingzhen Hao**[6,7], **Stefanie Kaboth**[8], **Daniel Veres**[9], **Frank Lehmkuhl**[2], **Milijoj B. Gavrilov**[4], **Slobodan B. Marković**[4]

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Loess-paleosol sequences represent the spatially most widespread geoarchives across Eurasia. Hence, the assessment of chrono- and lithostratigraphic patterns and differences of these terrestrial paleoclimatic records represents a key to unravel the climate evolution of Eurasia. Yet, the reconstruction of its climatic history is still challenging, i.e. due to time scale uncertainties and interpretation of paleoenvironmental proxy data. This represents a major limitation for understanding the interaction and evolution of Northern Hemisphere climate systems over the continental areas, and also their relation to marine proxy records. Inconsistencies and crucial issues concerning timing, correlation and interpretation of these loess-paleosol records are outlined.

In this study, we aim to investigate the effect of time scale (in)consistency for paleoclimatic interpretations of several loess-paleosol sequences from Eurasia. Firstly, we test the effect of different stratigraphical relationships/correlations by using original time scales, and correlations to different reference datasets. Secondly, we utilize linear mathematical models of reference datasets (including orbital parameters and a deep marine oxygen isotope record)- Then we compare the observed relationships to explain the patterns observed in loess paleoclimate data. This way the effect of alignment and different stratigraphic (age model) interpretations onto inferred origins of paleosol formation in loess records are compared. Finally, we draw conclusions on how important time scale alignment is for the interpretation of forcing mechanisms driving loess-paleosol sequence formation. The outlined approach represents a crucial contribution to achieve a common stratigraphic interpretation, and represents a step forward in overcoming current timing/age differences between different records.

# 8e) New insights into the Quaternary vegetation and climate history

Poster

## Reconstruction of hydrological and vegetation changes in northern Israel during the last 30,000 years by pollen and isotope analyses of plant leaf waxes

**Helen Clarissa Böttcher[1], Thomas Litt[1], Janet Rethemeyer[2], Enno Schefuß[3]**

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The southern Levantine region is located in the transitional climate belt of North-Atlantic-, and monsoonal- influenced climate systems. Comprising the arid-to-semi-arid climate boundary, the region is very sensitive to climate change. Besides climate-induced vegetation changes, shifts in vegetation can also be triggered by human activities. As the Levant is a possible migration corridor for early humans to Europe there is a long history of human settlement, stock farming and agriculture (e.g. the cultivation of olive (*Olea europaea*)).

There are several records in Israel (e.g. Dead Sea, Lake Kinneret) that show the correlation between palaeo-climate and its effects on palaeo-vegetation. However, some climatically critical time-intervals like the Younger Dryas are still under discussion.

The investigated maar lake Birkat Ram is located in the Golan Heights in northern Israel. The obtained sediment core comprises the last 30,000 years and hence covers the Pleistocene/Holocene transition. In this study we reconstruct vegetation as well as hydrological changes during the last 30,000 years by combining pollen with carbon and hydrogen isotope analyses of plant leaf wax lipids. The pollen record shows the shift of steppe and open habitat grasslands to a Mediterranean forest vegetation during the transition zone from Late Pleistocene to Holocene. Whereas the glacial is dominated by non-arboreal pollen (e.g. Polygonaceae, Poaceae, Chenopodiaceae), the early Holocene shows a significant increase in arboreal taxa like *Quercus ithaburensis*.

The ongoing carbon isotope analyses of long-chain n-alkanes will provide further evidence for vegetation changes of plants using the $C_3$ or $C_4$ photosynthetic pathway. We expect to find a similar pattern as observed in the pollen record. In addition, we analyze the hydrogen isotope composition of leaf wax lipids, which will reflect changes in hydrological conditions in this region.

Our findings will broaden the picture of climate evolution in the Levant and contribute to a robust multi-proxy reconstruction of palaeoenvironmental conditions at Birkat Ram.

Talk

## Paleolagoonal archives along the Arabian Sea reveal Holocene climate and sea-level variability

**Valeska Decker[1], Susanne Lindauer[2], Jessica Landgraf[1], Gösta Hoffmann[1]**

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Mangrove ecosystems are situated within low-energy areas of the intertidal zone along subtropical to tropical coastlines. They represent the transition zone of marine and terrestrial environments. These areas generate ecological niches with specific demands on their potential inhabitants. A community of specialists, flora, fauna and fungi, now build up the mangrove ecosystems, also called mangals. Mangroves are sensitive to certain environmental factors, including temperature, sea-level, $CO_2$ and precipitation. Rapid changes of climatic conditions are a serious threat to the highly adapted specimen living there. Only few can cope with larger shifts, most taxa decline or even go extinct. Changing in floral species composition over time can be detected by high-resolution pollen profiles of paleolagoonal deposits, identified in the subsurface stratigraphy of recent sabkha environments. Here pollen grains are often well preserved. Therefore, these areas provide ideal archives that can be utilised to reconstruct environmental changes. We focus on the coastlines of the Arabian Sea in the northern Indian Ocean, specifically the shores of Oman and western India. Climate variability within our study area is linked to the Indian Monsoon circulation. First field investigations were carried out along the shoreline of northeastern Oman in February 2018. The recent climate in Oman is arid and there are few mangrove forests. These are made up of only one species, *Avicennia marina*. This species is known to be the most tolerant mangrove plant in terms of environmental conditions.

Archaeological and sedimentological evidence suggests that mangroves in Oman were more widespread and also enriched in species at the transition from Early Holocene to Mid Holocene. Hence, either climate conditions were more humid at that time or sea-level was different. We carried out shallow subsurface coring and trenching within sabkha-environments. Some of them can be identified as former lagoons with fresh water supply and connection to the sea and thus they could have potentially been mangals. Here we successfully identified fine-grained paleolagoonal deposits of several metre thickness. Moreover, even root penetration can be determined and eventually some root remains were found including preservation of original organic material. Our dating approach is based on $^{14}C$-dating of molluscs and plant remains.

**Talk**

## Climate dynamics during Marine Isotope Stage 19 in Tenaghi Philippon (NE Greece)

**Tobias Fischer, Andreas Koutsodendris, André Bahr, Jörg Pross**

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The interglacial corresponding to Marine Isotope Stage (MIS) 19 (790–761 ka) is considered the best orbital analogue for the Holocene. To contribute to a better understanding of short-term climate variability during MIS 19 we present a new, centennial-scale-resolution pollen record from Tenaghi Philippon (NE Greece) covering the interval from late MIS 20 to late MIS 18 (804–721 ka ago). Our palynological data reflect repeated centennial-scale change from warm/humid to cold/dry climate conditions that occurred partially during full interglacial conditions (cold/dry events CDE-19/1 to CDE-19/4, CDE-18/1). They are documented in expansions of steppe taxa at the expense of temperate forest elements. Based on the temporal resolution of our data, both the climatic deteriorations and the recoveries after each event occurred on time scales between 110 and 1250 yrs. The comparison of our palynological results from Tenaghi Philippon with regional and global climate records shows that the climate variability during the cold/dry events CDE-19/2 to CDE-19/4 and CDE-18/1 was connected to variations in North Atlantic circulation as well as temperature and ice-sheet changes in the high northern latitudes. These factors influenced the vegetation and climate at Tenaghi Philippon via the climate systems of the North Atlantic and the high northern latitudes. One exception from this pattern is the cold/dry event CDE-19/1. Despite its strong expression at Tenaghi Philippon, it is only weakly expressed in the North Atlantic and in the Central and Western Mediterranean regions. The trigger for this event may be related to a reduction in boreal summer insolation that resulted in the expansion of sea ice and the polar vortex in the high northern latitudes. When a yet undefined threshold was crossed, the intensification of the polar vortex may have allowed intense outbreaks from the Siberian High that caused cold and dry conditions at Tenaghi Philippon. When comparing the vegetation records for MIS 19 and the Holocene at Tenaghi Philippon, it becomes clear that the present interglacial is characterized by locally warmer and more humid interglacial conditions. In addition, the present interglacial differs from MIS 19 through the absence of analogues for the intra-interglacial cold/dry event CDE-19/1 and the cold/dry event CDE-19/2 that marked the end of the MIS 19c interglacial. Potential reasons for this dissimilarity could be the smaller Holocene ice sheets and increasing atmospheric CO2 concentrations during the Late Holocene.

**Poster**

## Sedimentological and paleontological investigation of Holocene mangrove swamps in Oman

**Jessica Landgraf[1], Gösta Hoffmann[2], Valeska Decker[3]**

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Today's mangrove populations represent a legacy of the forests that occurred during the Holocene (Alongi 2008). This goes for the Sultanate of Oman as well, where there has already been research about archaeological traces of mangrove swamps (cf. Lézine et al. 2002 and Berger et al. 2013) indicating a more widespread distribution in the middle Holocene.

Mangrove trees only grow in the intertidal zone, a highly dynamic environment. They are able to minimize coastal erosion by reducing water movement leading to increased sedimentation (cf. Alongi 2008). Since sea level changes play a major role in growth and decline of mangrove forests, they are often used as a sea level indicator. Changes in mangrove ecosystems also reflect changes in precipitation and temperature. These climatic factors are related to global monsoonal circulation patterns.

From analyzing the soil sedimentologically and paleontologically occurrences of paleo-mangrove ecosystems may be further investigated and inferences about hydrodynamics can be drawn. In this study a site south of the city Sur was chosen for field work including 30 drillings and seven trenches. Granulometry and geochemical analysis were conducted, paleontological investigation of mollusks and foraminifera was complementing the information.

We aim to identify the mechanism of environmental changes within mangrove ecosystems. By reconstructing the development of mangrove swamps from the Holocene until today depending on environmental conditions such as local sea levels predictions for future changes of the ecosystem in Oman will be achievable.

**References**

Alongi, D. M., 2008: Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuarine, Coastal and Shelf Science, 76(1), 1-30.

Berger, J. F., Charpentier, V., Crassard, R., Martin, C., Davtian, G., & López-Sáez, J. A., 2013: The dynamics of mangrove ecosystems, changes in sea level and the strategies of Neolithic settlements along the coast of Oman (6000–3000 cal. BC). Journal of Archaeological Science, 40(7), 3087-3104.

Lézine, A. M., Saliège, J. F., Mathieu, R., Tagliatela, T. L., Mery, S., Charpentier, V., & Cleuziou, S., 2002: Mangroves of Oman during the late Holocene; climatic implications and impact on human settlements. Vegetation History and Archaeobotany, 11(3), 221-232.

Poster

## Monthly resolved sea surface temperatures of the tropical Indian Ocean for the last centuries inferred from coral-Sr/Ca measurements

**Maike Leupold[1], Miriam Pfeiffer[1], Takaaki Watanabe[2], Dieter Garbe-Schönberg[3], Lars Reuning[1], Chuan-Chou Shen[4,5]**

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Tropical corals can be used to reconstruct past changes of environmental parameters such as sea surface temperatures (SST), rainfall and nutrient content by measuring Sr/Ca and stable oxygen isotope ratios and can therefore help to visualize changes in past climate variabilities. However, a lack of coral data still limits the understanding of the relationship between interannual and decadal climate variabilities in the tropical Indian Ocean.

Here, we use three fossil massive Porites coral samples from the central Indian Ocean (Chagos Archipelago) to reconstruct past SST. One sample records 41 years of the Maunder Minimum (1675-1716), one records 31 years of the late Little Ice Age (1836-1867) and the third one is dated to the mid-19th to early 20th century (1870-1909) covering 39 years. The samples were subsampled at a monthly resolution for trace element analysis. Sr/Ca ratios were measured using an ICP-OES. The Little Ice Age record shows larger interannual to decadal variabilities than the 19th-20th century records whereas seasonal amplitudes become higher towards the end of the 19th century. The results may give evidence for several SST regime shifts in the central Indian Ocean during the last centuries which will have to be investigated further.

Poster

## A 150,000-Year Vegetation and Climate History: The New Dead Sea Pollen Record

**Andrea Miebach[1], Chunzhu Chen[2], Thomas Litt[1]**

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The Dead Sea is a salt lake in the Eastern Mediterranean that occupies the lowest depression on Earth. It witnessed a dynamic history with strong lake level variations and salinity changes. In addition, the Dead Sea region is a key site for investigating the history of mankind because it accommodates important archaeological remains of modern humans and Neanderthals. Yet, our knowledge about the paleoenvironment and particularly the vegetation history of the Dead Sea region was still fragmentary.

Here, we present new pollen data inferred from sediments of the Dead Sea. The sediments were recovered from the center of the lake in the frame of an ICDP campaign. They represent the longest continuous sediment record of the southern Levant. We investigated more than 250 m of the sediment core spanning the last interglacial-glacial cycle. The palynological results indicate the occurrence of Irano-Turanian steppe, Saharo-Arabian desert vegetation, and Mediterranean woodland. The abundance of these vegetation types changed through time in response to the climate conditions. The last interglacial was initiated by a warm and dry phase marking a pronounced environmental change. It was followed by a spread of drought-adapted trees and shrubs such as olive trees suggesting seasonally more available moisture. During the last glacial, seasonality was less extreme. *Artemisia* steppe gradually increased until MIS 2, which was the coldest phase of the investigated timeframe.

The study gains new insights into environmental responses of the Dead Sea region to climate variations in the past. It contributes towards our understanding of paleoenvironmental conditions in the southern Levant, which functioned as a principal corridor for human migration processes.

Talk

## Zooming into inter-annual climatic variations from marine and lacustrine sediments: presenting a novel approach in ultra-high-resolution lipid biomarker-based paleoclimate research

**Igor Obreht[1], Lars Wörmer[1], Susanne Alfken[1], Jenny Wendt[1], Marcus Elvert[1], Julius S. Lipp[1], Verena B. Heuer[1], Heidi Taubner[1], Pier Luigi Buttigieg[2], Kai-Uwe Hinrichs[1]**

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Lipid biomarker analysis from marine and lacustrine core samples is a fundamental method in paleoclimate and paleoenvironmental research. However, sampling resolution in the cm-range required for conventional biomarker analysis is the main limiting factor for high-resolution temporal (seasonal to sub-decadal) past climatic and environmental reconstruction. Advances in mass spectrometry imaging (MSI), a technique used to visualize target molecules on sample surfaces at ultra-high spatial resolution on the µm-scale, showed a potential to overcome this problem. In paleoclimate reconstruction this technique was first introduced by Wörmer et al. (2014), where

(matrix-assisted) laser desorption/ionization coupled to Fourier transform-ion cyclotron resonance mass-spectrometry (MALDI-FT-ICR-MS) was applied on intact sediment sections. With current advances in sample preparation, this method holds a potential to revolutionize paleoenvironmental biomarker research.

Here we present lipid biomarker results from MALDI-FT-ICR-MS applied on marine and lacustrine records with established robust age-models. Obtained information are indicative of valuable paleoclimate signals, such as sea surface temperature changes and vegetation evolution. With the acquired unprecedented temporal resolution, we can explore the interdependence between inter-annual and decadal climatic variability, the environmental response to high-frequency climatic variations, and the potential impact of solar forcing. Understanding of lipid biomarker distribution with such high-resolution potentially enables for reconstruction of previously hardly detectable periodic climatic oscillations, such as El Niño-Southern Oscillation and North Atlantic Oscillation, study their climatic teleconnections and evaluate its influence on global climate change, as well as understand their impact on the environment.

Reference:

Wörmer, L., Elvert, M., Fuchser, J., Lipp, J.S., Buttigieg, P.L., Zabel, M., Hinrichs, K.U., 2014. Ultra-high-resolution paleoenvironmental records via direct laser-based analysis of lipid biomarkers in sediment core samples. Proc. Natl. Acad. Sci. 111, 15669-15674.

Poster

## Preliminary Results of Volcanic Impacts on Ecological Systems Based on Annually Laminated Sediments from Lake Van, Turkey

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*University of Bonn, Germany*

One of the major problems with palaeoclimate investigations in volcanic regions is that tephra inputs to lakes can cause changes in proxies analogous to those of climate forcing. In general, volcanic eruptions are well-known driver of short-term climate variations and thus responsible for rapid changes in local vegetation. Ecological research about volcanic impacts is mostly based on observations made several decades after the eruption. Studies of the environment following the St. Helens eruption have shown that the affected vegetation outside the blast zone recovers rapidly within years (Del Moral and Bliss, 1993. *Adv. Ecol. Res*. 24:1-66).

In this preliminary study, we review the range of direct effects on terrestrial and aquatic vegetation to environmental perturbation on major tephra layers in Lake Van sediments. To archive a better understanding of these complex responses, we have used high-resolution pollen analysis (mean resolution: 3.5 years) based on annually laminated sediments. In this highly sensitive region, the Nemrut and Süphan volcanoes have been the most frequent source of tephra for the last 400 ka at Lake Van. Such disturbances provide the opportunity to study past ecological dynamics with respect to rate of vegetation change, reaction time, plant regeneration, and changes to catchment processes. Based on this, we want to know how the semi-arid steppe vegetation at Lake Van responds to volcanic impacts. Do we see, as expected from other ecological research of volcanic impacts, an increase of light-demanding taxa (e.g., *Juniperus*) and steppe elements (e.g., *Artemisia*, Chenopodiaceae), a reduction in the biodiversity, or perhaps a positive correlation to fire events? Do we recognize an immediate reaction in the abiotic proxies, such as an increase in erosion by XRF measurements or even a significant change in annual accumulated sediments?

This preliminary study at Lake Van can help to evaluate the course and mechanism of vegetation changes after volcanic disturbances in a sensitive climatic region.

Talk

## The late Holocene, high-resolution storm and climate archive of the Blue Hole, Lighthouse Reef, Belize (Central America)

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Based on climate data of the Atlantic region, the strength and destructiveness of tropical cyclones (TC) has been increasing in the 20th century. However, there is still the need to extend this data set beyond instrumental climate time-series. It is very important to gain a better understanding of long-term patterns of TC-frequency and intensity because cyclones represent a substantial threat to life and property. Storm archives are rare and often controversial. A highly suitable marine record from the western Caribbean basin that possesses annual resolution is the sediment succession at the floor of the Great Blue Hole of Lighthouse Reef in Belize, which comprises fine-grained, varved background sediments and intercalated sandy event beds. A new 7.81 m long vibrocore offers the opportunity to analyze Caribbean cyclone activity and climate back to 400 CE. In addition to pure counting of storm layers, systematic and statistic estimation of event-layer thickness, grain size and frequency is in progress. The rise in mean sea-surface temperature plays a major role in Caribbean long-term patterns of TC-frequency and intensity. Our data show that an increased frequency (return period of 16 years per century) was observed during times of elevated and/or rising temperatures such as the modern global warming interval since 1800 CE. During the Little Ice Age (1800 CE–1400 CE), the frequency was much lower with a mean return period of 33 years. The Blue Hole record also shows that elevated storm frequency appears to coincide with the Medieval Warm Period (1400 CE–700 CE). The mean return periods are similar to, or in parts even shorter (11 years per century), as compared to the recent global warming. Wavelet analysis indicates three cycles (150, 100 and 56 yr) affecting the TC-frequency. Especially the 56 yr cycle, which occurs mainly during the entire Medieval Warm Period, likely suggests a connection between the Atlantic Multidecadal Oscillation (AMO) and hurricane frequency. The evaluation of eventlayer thickness as a proxy for tropical cyclone intensity shows a similar pattern with stronger TC-events during relatively warm intervals. Wavelet analysis for TC-intensity is less significant, but the positive feedback effects of AMO (56 yr) are still visible, especially for the entire Medieval Warm Period. Interestingly, our data indicate more frequent and stronger tropical cyclones during the naturally forced Medieval Warm Period as compared to the anthropogenically forced industrial era.

**Poster**

## How can we combine model and proxy data for paleoclimate reconstructions?

**Sophie Stolzenberger, Andreas Hense**

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The German interdisciplinary research program “Our way to Europe“ (CRC 806) studies the history of the Modern Man by investigating the main migration routes from Africa to Europe. One focus of the project is the reconstruction of past climate states for Europe.

Paleoclimate model simulations, which were performed within the PMIP3 (Paleoclimate Modelling Intercomparison Project Phase 3) framework, provide regional climate information determined by global forcings like insolation or greenhouse gase concentrations. The results can mostly be evaluated by proxies only. Suitable proxies are pollen, with which statistical botanical-climate transfer functions can be estimated. These probabilistic information based on pollen can be used to evaluate and optimize paleoclimate model simulations. The advantage is that we obtain spatial climate reconstructions based on both models and proxies. This method will be presented in detail and characteristics will be discussed.

We apply this method to Mid-Holocene (6 ka BP) temperatures. For summer, assimilating a PMIP3 multi-model ensemble to observed pollen data indicates a temperature increase relative to the model simulations. These results are supported by predominantly positive Brier skill scores.

**Talk**

## Onset of continentalisation in the circum-Black Sea region during the latest Miocene: a multiproxy approach

**Iuliana Vasiliev[1], Angelica Feurdean[1], Gert-Jan Reichart[2,3], Andreas Mulch[1,4]**

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The present day Black Sea represents the sink for some of the largest European rivers. The Black Sea basin acted as water and sediments sink since geological times, when it was a part of the Eastern Paratethys, an epicontinental sea covering substantial regions on the Eurasian interior. Previous investigations revealed several phases of strongly enhanced evaporitic and dry conditions in the late Miocene. Here we present the first time record of continental temperature, soil type and biomass burned changes in the circum-Black Sea region during the late Miocene to the transition into Pliocene (from ~10.0 to 5.0 Ma). We use branched glycerol dialkyl glycerol tetraether (brGDGT) for the reconstruction of the mean annual air temperature (MAAT) and soil pH of the land mass and charcoal morphologies to determine interactions between climate and biomass burned . Based on our MAAT record, a generally decreasing temperature trend was recorded between ~10 and 7.5 Ma. Our record of soil types indicate acidic soils for the time interval between ~10 and 7.5 Ma, which is in line with pollen-based vegetation reconstruction of mega- and mesothermic trees dominance in the Black Sea region. The Pontian flooding at 6.12 Ma brought a large quantity of organic debris and charcoal fragments indicating that was a forceful event. A sharp cooling record at 840 mbsf coincided with the TG 20 and TG 22 glacial peaks at 5.8 Ma. The negative water budget affecting the Mediterranean Basin has influenced the vapor (i.e. precipitation) availability in the entire circum-Mediterranean. For the interval between 5.8 and 5.0 Ma, the source for the brGDGTs is dominantly from north of Black Sea, likely from a cold steppe environment. Decrease fire activity at the time of cooler temperature and higher proportion of grasslands, give support for increased continentally between 5.8 and 5.0 Ma. Our data pin down the large environmental changes affecting the continental realm around the Black Sea during the latest Miocene and the transition into Pliocene when alterations in connectivity to the ocean led to quasi-isolation and shrinkage of the Paratethys Sea of Eurasia

Poster

## Lake Kinneret (Israel): New insights into Holocene regional palaeoclimate variability based on high resolution multi-proxy analysis

**Hannah Vossel[1], Patricia Roeser[2], Thomas Litt[1], Jane M. Reed[3]**

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Although the Eastern Mediterranean and especially the southern Levant are key regions for paleoclimatological and paleoenvironmental research, our understanding of Holocene environmental variability and its possible drivers is still limited. As diatoms remain one of the least-exploited proxies in paleoclimate research in the Mediterranean region, we would like to present a high-resolution multi-proxy record (special emphasis is given to diatom analysis) from Lake Kinneret (the Sea of Galilee), Israel.

During the Holocene, well-correlated shifts in the diatom, minero-geochemical and palynological data indicate marked lake-level variation over time as well as changes in the trophic state of Lake Kinneret. Our results are particularly important in improving the reconstruction of Holocene lake-level variation, and thus past moisture availability. Diatom-inferred lake-level oscillations correlate well with the output from climatic models from the Levantine region and clarify previous uncertainty concerning regional variation in moisture availability. The Early Holocene (from ca. 9,000 cal yrs BP to 7,400 cal yrs BP) was characterized by lake-level shifts due to fluctuating dry-wet climate conditions. During the mid-Holocene (from 7,400 to 2,200 cal yrs BP), a stable, deep lake-level phase persisted due to high humidity. The lake level of modern Lake Kinneret fluctuates seasonally with available moisture, but has also been influenced for ca. 2,000 years by the impacts of water abstraction for human consumption and agriculture.

Over the last 9,000 cal yrs BP, the trophic state of Lake Kinneret has changed from an oligotrophic to a meso- to eutrophic environment, mainly triggered by increased human impact from around 2,200 cal yrs BP onwards. The lake's ecosystem status was not strongly affected by the documented major changes in human occupation patterns during the mid-Holocene, when a relatively stable environment persisted.

Poster

## Raman spectroscopic investigation of mechanisms of calcite-aragonite transitions of a Holocene high-alpine stalagmite from Central Switzerland

**Martin A. Ziemann[1], Jens Fohlmeister[1,2], Martin Trüssel[3]**

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Stalagmites have established as recorders of climate variability. They can grow up to several thousands of years, their climate information is well preserved due to their protected environment and they can be precisely dated by means of U-Th disequilibrium methods. Generally, a large toolbox of common proxies is available to reconstruct climate variability.

Here, we investigate the potential of a new proxy to decipher climate information from calcite (Cal) to aragonite (Arg) transitions in a stalagmite found in the northern rim of the Swiss Alps. This stalagmite is already well investigated in terms of its U-Th based chronology and its stable isotope composition. The Cal-Arg transitions occurred along the growth axis and laterally, along individual growth layers. Especially the lateral type of transitions occurs only very rarely in natural carbonates. However, they provide the potential to study the mechanisms responsible for the polymorph change during precipitation from carbonate containing solutions. We applied high resolution Raman spectroscopic mapping on the Cal-Arg transitions. This method reveals that Arg-Cal transitions occur abruptly, starting from single Cal nucleation seeds within a closed Arg layer and spreading fan-like in growth direction to build within less than ~50 µm a closed Cal layer. Transitions from Cal to Arg occur not as abrupt as the Arg to Cal transitions, as single Cal structures seem to stop growing at various locations and are replaced by Arg needles.

# Topic 9: Earth materials, resources, and waste management

## 9a) Geoscientific aspects of the safe management of mineral, hazardous and nuclear wastes

Poster

### Recovery of heavy metals from industrial wastewater – challenge of upscaling lab-scale experiments

**Iphigenia Anagnostopoulos, Johannes Knof, Soraya Heuss-Aßbichler**

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Many industrial effluents pose a serious environmental problem due to their high heavy metal contents. Conventional purification methods produce highly voluminous, in general environmentally hazardous hydroxide sludges, the disposal of which can be costly (LoW No. 110109). Recently, the economic loss of these heavy metals as a valuable resource is increasingly becoming aware.

An interesting approach was provided by the so-called ferrite process, which was originally developed for the treatment of laboratory effluents. We modified this precipitation process, by selectively using the various reaction parameters to control the composition of precipitation products, now referred as “SPOP - a specific product - oriented precipitation”. The results of the laboratory scale experiments have demonstrated the efficiency of the SPOP process to recover Cu, Zn, Au, Ag, Ni, Pd, Sn, Pb, Mn und Cr from wastewater. The heavy metals are precipitated as zero-valent phases (e.g. $Au^0$), oxides with ferrite structure (e.g. $(Zn, Ni, Cu, Fe, Mn)^{2+}Fe^{3+}{}_2O_4$) or delafossite structure (e.g. $CuFeO_2$), and doped heavy metal oxides (e.g. $Cu_2O$, ZnO). At optimal conditions, the recovery rates are better than 99.9 %. The results show that wastewater treatment as a novel technology for the recovery of heavy metals as secondary raw materials can be economically viable.

To test the feasibility of the SPOP process for industrial throughput rates (e.g. 100 l/h) we developed a portable pilot plant. The system is built in an easily moveable roller frame with a base area that corresponds to the standardized euro-pallet size. With a total weight of less than 800 kg, it can be easily transported. For the upscaling of the facility, all components of the laboratory installation were examined regarding material selection, robustness, and its implementation into the automation process. The selected materials of the components also allow the treatment of abrasive fluids. With our pilot plant, a large spectrum of different industrial wastewater can be treated within the range of pH 2 – 12. The temperature for the precipitation process can be set to a maximum of 70°C. The modular design of the prototype facilitates the adaptation of the precipitation process to the different requirements of different branches of industries. The pilot plant can be operated in an automatic control mode; but it can also be controlled manually at any time.

The research is funded by the Bavarian State Ministry of the Environment and Consumer Protection.

Poster

### Mineralogy and leachability of V, Cr, Cu, Mo, Ni and F from natural rocks: six examples from Austria

**Maximilian Berger[1], Simone Neuhold[2], Philipp Szedlazeck[2], Daniel Vollprecht[2], Johann Raith[1]**

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Mined natural rocks used as construction material can be substituted by recycled materials and industrial aggregates, e.g., steel slags. The use of these materials is subjected to the Austrian recycling regulation (RBV) and hence restricted by limits for total contents and leaching concentrations of several environmentally critical elements. Natural rocks are not subjected to such limits although they can similarly be enriched in heavy metals. In this study, which is conducted within the project MiLeSlag (Mineralogy and Leachability of Steel Slags), six Austrian rock samples were investigated concerning their mineralogy and their total and leachable contents of V, Cr, Cu, Mo, Ni and F (ICP-MS, IC, photometry). Chemical composition of the phases was determined by electron probe microanalysis (EPMA). The leachability of environmentally relevant elements from two samples was determined by pH-dependant leaching tests (EN 14429) and percolation tests (according to EN 14405). Hydrogeochemical modelling using LeachXS™ was applied to suggest the phases which control the leachability.

One orthogneiss sample contains 49500 mg/kg Mo which is present as molybdenite. From this sample 2.5 mg/kg Mo were leached at natural pH which is five times higher than the limit value for slags in road construction. A serpentinite sample contains 3011 mg/kg Cr which exceeds all limits of the RBV. In this sample Cr is mainly present in chromian spinel but also in serpentine and chlorite. A small portion 0.24 mg/kg Cr was present as Cr(VI). Leaching of Cr accounted only for 0.003 mg/kg, which is below all limits of the RBV. Hydrogeochemical modelling confirmed that the extremely low leaching of Cr is controlled by the low solubility of the spinel phase. In the serpentinite sample, total Ni contents of 2580 mg/kg and leaching concentrations of 1.1 mg/kg are clearly above the limit values for recycled and industrial aggregates; Ni is incorporated in olivine and serpentine.

Contrary to hydrogeochemical modelling and mineralogical observations, which indicated the incorporation of both Ni and Cr (in serpentinite) and Mo (in orthogneiss) in mineral phases, percolation tests showed decreasing release of these elements over time which suggests desorption rather than dissolution as the main factor controlling leachability. However, clogging of pores by secondary mineral phases might have decreased the release of these elements physically during the course of percolation tests. Our study demonstrates that heavy metals may not only be enriched in natural rocks, but are also leached in concentrations above limits for industrial or recycled aggregates.

**Talk**

## Synthesis and characteristics of chromium doped $UO_2$-based model materials for single effect studies to understand the long-term matrix corrosion of spent nuclear fuels under disposal conditions

**Felix Brandt, Philip Kegler, Steve Lange, Martina Klinkenberg, Andrey Bukaemskiy, Guido Deismann, Sarah Finkeldei, Evgeny V. Alekseev, Dirk Bosbach**

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An in-depth understanding of the long-term behaviour of spent nuclear fuel (SNF) in a deep geological disposal facility (GDF) and knowledge of radionuclide release mechanisms under relevant conditions are indispensable requirements for demonstrating the long-term safety of the repository. Although the improved in-reactor performance of modern Cr- and Al-doped light water reactor (LWR) fuels has already successfully been demonstrated, it is still not known, whether the corrosion behaviour of such fuels in a GDF is similar to conventional spent LWR-fuels. However, due to the chemical and structural complexity of SNF and its high beta- and gamma radiation field, experiments with SNF cannot unravel all of the various concurring dissolution mechanisms entirely. Thus in order to understand how the addition of Cr- or Al-oxide into the fuel matrix affects SNF dissolution behaviour under repository relevant conditions, within the EU-DISCO project (www.disco-h2020.eu) experiments on irradiated doped fuels are complemented with dissolution studies carried out with systematically produced and carefully characterised $UO_2$-based model materials. These single-effect studies on the dissolution behaviour of the model materials will provide complementary insights and supporting process understanding regarding the performance of modern doped fuels in the repository environment, which cannot be directly obtained from SNF studies.

In this presentation, we provide an overview on the development and optimisation of the synthesis route for the production of pure and Cr-doped $UO_2$ model materials to be used in the planned dissolution experiments. This method has also to be suitable for the later production of alpha-doped Pu-containing materials. Therefore the synthesis was performed by coprecipitation and wet-coating methods and had to be free of any grinding steps to prevent dust generation. In order to provide insights into the effects of the material's microstructure on the dissolution behaviour (e.g. regarding the larger grain size in doped fuels and contributions of grain boundaries) the model materials are produced in form of sintered pellets. The microstructure (grain size, grain orientation of and dopant distribution (i.e. either in solid solution within the $UO_2$ matrix or segregated on grain boundaries) in the model materials were characterised using various methods (e.g. SEM, EBSD, EMPA, ToF-SIMS, XRD). Moreover, first results regarding the dissolution behaviour of these materials in accelerated static batch experiments using $H_2O_2$ as simulant for radiolytic oxidation products will be presented.

**Poster**

## Micro-continuum simulation of Ra-226 migration in fractured crystalline rocks: Application of High Performance Computing to evaluate effects of intrinsic system heterogeneity at the micrometer scale

**Guido Deissmann[1], Paolo Trinchero[2], Jorge Molinero[2], Ignasi Puigdomenech[3], Björn Gylling[3], Jenna Poonoosamy[1], Dirk Bosbach[1]**

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Deep geological disposal facilities (GDF) for high-level nuclear waste are based on multi-barrier concepts, combining an engineered barrier system with a suitable repository host rock. The migration of radionuclides from a GDF into the geo-/biosphere occurs mainly via the water pathway, after the waste comes into contact with groundwater, subsequently to failure of the waste canisters. In crystalline rocks, radionuclide migration is controlled by advection along fractures and diffusion into the rock matrix, and affected by various retention mechanisms such as sorption, precipitation/dissolution of discrete phases, as well as entrapment in or solid solution formation with other solids. For the post closure safety assessment of a GDF, fundamental insights into the processes governing radionuclide migration from molecular level up to the macro-scale are required, including an understanding of effects introduced by process couplings and system heterogeneity.

In-situ and laboratory investigations provided evidence of the highly heterogeneous nature of the matrix of crystalline rocks with respect to microstructure and distribution of available mineral surfaces. This heterogeneity was suggested as explanation for anomalous (radio) tracer penetration profiles observed in experiments at the ONKALO underground research facility in Finland and the Äspö Hard Rock Laboratory in Sweden, and to explain discrepancies between the results of continuum-scale simulations and observations. Here, we used a synthetically generated fracture-matrix system to analyse the effects of the intrinsic grain-scale mineralogical heterogeneity of the rock matrix on processes affecting radionuclide migration, applying a micro-continuum reactive transport model. Specifically, the retention of Ra-226 due to the solid solution formation with barite ($BaSO_4$) was addressed, which is deemed an important retention mechanism for

Ra-226 and used as a solubility constraint in some safety assessments for spent nuclear fuel disposal. Due to the high computational demands, these simulations were performed on the supercomputer JUQUEEN at the Jülich Supercomputing Centre, using the massively parallel reactive transport code PFLOTRAN. The results of these simulations contribute to a refined understanding of the effects of the intrinsic heterogeneity of the rock matrix on processes controlling radionuclide migration in fractured crystalline media. Moreover, they may serve as a starting point for the development of approaches to represent system heterogeneity on multiple scales and for upscaling strategies for larger-scale reactive transport models, thus providing a more realistic view on the evolution of a repository system.

**Talk**

## Mineralogy and geochemistry of biomass-combustion waste

**Reto Gieré[1], Christoph Maschowski[2]**

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Combustion of solid biomass to produce electrical power and heat plays an important role in the transition from fossil and nuclear fuels to renewable energy sources. Solid biomass fuels consist mostly of waste products from forestry (mainly wood) and agriculture (mainly straw).

Solid biomass contains various inorganic components, which differ in amount and speciation depending on, e.g., plant type, soil, and harvest season. These inorganic components are non-combustible and accumulate as ashes after combustion. One portion mostly stays at the combustion grate as bottom ash; the other is carried out of the boiler as fly ash with the flue gas. In modern combustion devices, air pollution control devices, such as, cyclones and electrostatic precipitators, remove a significant amount of this fly ash from the flue gas, with the remainder released into the atmosphere. The quantities, physical properties, and chemical composition of these fractions strongly depend on combustion parameters, including temperature, extent of combustion, and fuel type, which also determine the amount of unburned carbon left after the combustion process. Incomplete combustion typically leads to the formation of considerable amounts of soot and organic compounds, such as, polyaromatic hydrocarbons (PAH) and tar, which both can be hazardous for living organisms.

Bottom ashes and, in large-scale combustion facilities the fly ashes as well, are usually treated as waste products. Bottom ashes are considered unproblematic materials and sometimes are used as fertilizer additives, because they also contain valuable nutrients. Fly ashes, on the other hand, may be enriched in heavy metals and therefore have to be discarded as problematic waste. Characterization of a wide range of biomass ash types can help in assessing the risk or potential, especially when it is crucial to return ashes from biomass combustion to the soil to avoid depletion of nutrients. We will present mineralogical and geochemical data for various types of ashes and discuss the potential of using these ashes as a secondary raw material in the cement industry.

**Poster**

## An innovative process chain for recovering metals from ashes and slags

**Amanda Günther[1], Martin Wachsmann[1], Christoph Faist[1], Sebastian Dittrich[2], Volker Thome[2]**

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The solid residues produced during municipal solid waste incineration (MSWI) and metallurgical processes generate more than 19 million tons of bottom ashes, aerial pollution cleaning residues and slags in Germany. Common to all is the high reusable potential of mineral and metallic components. Especially the fine portion of those materials contains metals like antimony, tin, molybdenum, cobalt and rare earth elements e.g. lanthanum, cerium and yttrium which are classified as „critical raw materials "by the EU commission (EU2010). The project ELEXSA addresses these processing residues within an innovative process chain. In the first step, the materials were selectively separated by electrodynamic fragmentation. The process is based on ultra-short (< 500 nsec) pulsed underwater discharges. On the way to the counter electrode the electric discharge runs through the material along phase boundaries. The composite material is broken down by a shockwave (p ~ 1 GPa) generated when the discharge reaches the counter electrode. As the composite is pre-weakened along phase boundaries a selective decomposition of the material is obtained (Dittrich et al., 2017). In the next step, the fine material, in which the critical raw materials are accumulated, is processed hydrothermally to solve the hardly soluble metals. Under hydrothermal conditions hardly soluble metals can be solved at elevated temperatures and pH-values (Günther et al., 2014). The solution process is mainly controlled by ionic strength of the solvent next to surface and mineralogical and chemical phase composition of the material. In the ELEXSA project, 7 different samples -2 from secondary metallurgical processes and 5 from MSWI-plants- were electrodynamically and hydrothermally treated. Solving experiments were performed under hydrothermal conditions at a temperature of 165°C for 2 h under saturated steam pressure, by using a solid / liquid ratio of 1:16.5. Solution kinetics were studied depending on pH-values. The materials have been characterized mineralogically, chemically and physically by X-ray powder diffraction (XRDF), X-ray fluorescence analysis (XRF, µ-XRF), scanning electron microscope equipped with energy dispersive X-ray (SEM-EDX), Fourier transformed infrared spectroscopy (FTIR), laser particle sizer (LS) before and after the hydrothermal experiments. The solutions produced by hydrothermal experiments were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES). All investigated samples show a lower content in the fine region of the particle size measurements. This indicates that the fine portion of the samples has been solved. Solubility of metals depends strongly on the mineralogical phase composition as well as on the pH-value. Low pH-values favor higher solution rates.

**Poster**

## Radiation effects in Sm-monazite – a potential waste matrix for plutonium and minor actinides

**Julia M. Heuser[1], Yaqi Ji[2], Martina Klinkenberg[2], Piotr M. Kowalski[2], Hartmut Schlenz[2], Stefan Neumeier[2], Dirk Bosbach[2], Guido Deissmann[2]**

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During the last decades, various ceramic materials have been proposed as potential waste forms for the immobilization of special nuclear waste streams, such as separated plutonium from civilian sources, excess weapons plutonium, or separated minor actinides (MA: Np, Am, Cm). Among them, monazites (monoclinic $LnPO_4$) are seen as promising candidates due to their specific properties including high structural flexibility for actinide incorporation, high chemical durability, and high radiation resistance. One of the key issues for crystalline ceramic waste forms in general concerns potential property changes in response to radiation-induced phase transformations, due to the alpha decay of the incorporated actinides. Radiation damage due to self-irradiation in ceramic waste forms is caused mainly by the recoiling nuclei and to a lesser extent by the emitted alpha particles.

This study focuses on radiation-induced effects in Sm-monazite with respect to its long-term performance in the repository environment. Heavy ion bombardment experiments were performed on $SmPO_4$ to simulate ballistic effects similar to those resulting from recoiling nuclei during alpha-decay. Therefore, the Sm-monazite samples were irradiated with Au ions with energies of 1, 3.5, and 7 MeV up to fluences of $5.1 \cdot 10^{14}$ ions·cm$^{-2}$. Besides the irradiation experiments, computational simulations using SRIM/TRIM were performed for interpretation and support of the experimental findings. Since experimental data on threshold displacement energies ($E_d$) are lacking for monazites so far, the respective $E_d$-values for all atoms in the Sm-monazite structure were derived from intensive molecular dynamics simulations using the LAMMPS code.

Irradiation with fluences up to ~$2 \cdot 10^{13}$ ions·cm$^{-2}$ produced only minor structural changes in the $SmPO_4$ lamellae, whereas vast amorphisation was observed for the maximum fluence. However, even in this case the material was not completely amorphised due to local annealing effects leading to the formation of recrystallised domains. Studying the Raman band broadening suggests that the amorphisation of monazite is mainly due to the breaking of Ln-O bonds while the $PO_4$ tetrahedra behave as a rigid unit. Annealing effects that can be observed already during irradiation experiments at ambient temperature, the fact that dose rates occurring in an actinide bearing waste matrix would be significantly lower compared to ion beam irradiation as well as the potential additional annealing effect of alpha-radiation emphasise the high potential of Sm-monazite as a suitable actinide waste form capable of withstanding amorphisation.

**Poster**

## The Solid Solution – Aqueous Solution System $(Ba,Sr,Ra)SO_4$ + $H_2O$ at Sr-rich Compositions

**Martina Klinkenberg[1], Juliane Weber[1], Juri Barthel[2,3], Victor Vinograd[1], Jenna Poonoosamy[1], Dirk Bosbach[1], Felix Brandt[1]**

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Solid solution formation is an important mechanism of radionuclide uptake by mineral phases in aqueous environment which is favored in natural systems due to an increase in the configurational entropy. Recent studies have shown that the formation of a $(Ba,Ra)SO_4$ solid solution significantly reduces the solubility of $^{226}Ra$ in aqueous solution at ambient conditions. These results are relevant for the direct disposal of spent nuclear fuel in deep geological formations, where in some scenarios $^{226}Ra$ may dominate the dose after $10^4$ - $10^5$ years [1]. In natural systems barite ($BaSO_4$) often occurs along with celestine ($SrSO_4$) implying that Ra-uptake should be assessed within the solid solution – aqueous solution (SS-AS) system of $(Sr,Ba,Ra)SO_4$ + $H_2O$. A recent thermodynamic modelling study [2] predicted a significant uptake of Ra into the ternary $(Sr,Ba,Ra)SO_4$ solid-solution.

Here, we combined experiments, atomistic simulations, and thermdynamic modelling to evaluate the Ra-uptake at Sr-rich compositions within the ternary SS-AS system $(Sr,Ba,Ra)SO_4$ at 90 °C. A mechanical mixture of celestine (99 mol%) with a small amount of barite (1 mol%) and a $(Sr_{0.99}Ba_{0.01})SO_4$ solid solution of equivalent composition were put into contact with a $^{226}Ra$ containing solution ($5 \cdot 10^{-6}$ mol/L $RaBr_2$) for 1302 days. The experimentally observed final $Ra_{aq}$ concentration which is about one order of magnitude lower compared to the initial concentration indicated an efficient uptake into the newly formed solid phases. These final $Ra_{aq}$ concentrations appeared to be marginally lower than those predicted by thermodynamic calculations. This implies that the thermodynamic equilibrium was close to be reached in the studied Sr-rich systems.

The recrystallization process of the solids was followed by scanning electron microscopy with energy-dispersive X-ray spectrometry (SEM-EDX), focused ion beam (FIB) and transmission electron microscopy (TEM). Several metastable phases, starting from the least soluble, Ba- and Ra-rich precipitates and ending with Sr-rich solids, which compositions approached the predicted equilibrium states, were observed. This evolution was correlated with changes in the computed supersaturation functions. Particularly, the formation of Ra-, Ba- and Sr-rich rims on primary barite grains in the experiments with the mechanical mixture was explained by combining calculated supersaturation conditions with considerations of structural misfit.

[1] SKB (2011). Long-term safety for the final repository of spent nuclear fuel at Forsmark Main report of the Sr-site project I-III. Stockholm, Sweden.

[2] Vinograd et al. (2018). Applied Geochemistry, 93, 190-208.

Talk

## Glass Corrosion: Towards a unifying mechanistic model

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Borosilicate glasses are currently used for the immobilization of highly radioactive waste and are materials of choice for many biomedical and research industries. They are metastable materials that corrode in aqueous solutions, reflected by the formation of silica-rich surface alteration layers (SAL). Until now, there is no consensus in the scientific community about the reaction and transport mechanism(s) and the rate-limiting steps involved in the formation of SALs. Here we report the results of multi-isotope tracer (2H,18O,10B, 30Si, 44Ca) corrosion experiments that were performed with precorroded and pristine glass monoliths prepared from the six-component international simple glass and a quaternary aluminum borosilicate glass. Nanoscale secondary ion mass spectrometry analyses revealed the decoupling of 18O and 2H at a phase boundary between a silica-based SAL and the underlying glass, suggesting the diffusion of protons into the glass while molecular water was retained at the glass surface. The diffusion of 2H into the glass was found to coincide with the outward diffusion of Na+. Transmission electron microscopy further revealed a dense silica layer at the interface between SAL and the leached glass. In one precorroded sample, an additional dense layer was identified within the SAL, suggesting that this layer is a relic of the precorrosion step and thus a quench layer that formed from an interfacial (pore) solution. We propose a unifying mechanistic model that accounts for all critical observations so far made on naturally and experimentally corroded glasses. It is based on an interface-coupled glass dissolution-silica precipitation (ICDP) reaction as the main SAL forming process. However, a diffusion-controlled ion exchange front may evolve in the glass ahead of the ICDP front if SAL formation at the reaction interface significantly slows down due to transport limitations.

Poster

## Iodine in metal organic frameworks at high pressure

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Capture of highly-volatile radioactive iodine is a promising application of metal organic frameworks (MOFs), thanks to their high porosity with flexible chemical architecture. Specifically, strong charge-transfer binding of iodine to the framework enables efficient and selective iodine uptake as well as its long-term storage. As such, precise knowledge of the electronic structure of iodine is essential for a detailed modelling of the iodine sorption process, which will allow for rational design of iodophilic MOFs in the future. Here we report on the electronic structure of iodine in MOFs at variable iodine···framework separation as probed by Raman and optical absorption spectroscopy at high pressure (*P*). The electronic structure of iodine in the straight channels of SBMOF-1 (*Ca-sdb, sdb = 4,4`-sulfonyldibenzoate*) is modified irreversibly at *P* > 3.4 GPa by charge-transfer, marking a crossover in iodine chemical speciation. In contrast, iodine in the sinusoidal channels of SBMOF-3 (*Cd-sdb*) retains its molecular character up to at least 8.4 GPa. Such divergent high-pressure behavior of iodine in the MOFs with identical pore size and chemistry suggests that the electronic structure of iodine is not constant but adapts to channel geometry and strength of the iodine···framework interaction. Our results exemplify that the topology of the sorption surface is another important factor governing the efficiency of iodine uptake by porous solids.

Poster

## The effect of heavy ion irradiation on the dissolution rate of borosilicate glasses studied in real-time by in situ Raman spectroscopy

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Borosilicate glasses are the favoured material for immobilization of high-level radioactive waste (HLW) from the reprocessing of spent fuel used in nuclear power plants. To assess the long-term stability of nuclear glasses, it is critical to understand the structural irradiation effects and their impact on the glass dissolution properties. Self-irradiation damage induces bond-breakage and atomic displacements by two distinct mechanisms: radiolysis (principally from energetic beta-decay electrons) and ballistic mechanisms. Alpha decay produces mainly ballistic-type collision damages by the α-recoil nuclei while the released alpha-particle predominately deposits its energy by ionization processes. In silicate glasses, self-irradiation causes depolymerisation and an analogous increase of the entropy, which are potential factors affecting the long term stability. For this study, a ternary borosilicate glass was irradiated with gold ions with an energy of 890 MeV and fluence of 5x1012 ions/cm² to study the effect of the glass structure on the forward dissolution rate. The penetration depth of the ions was about 48 µm. A Horiba Scientific HR800 Raman spectrometer equipped with a 2W Nd:YAG laser (532.09 nm) and an electron-multiplier CCD detector was used to characterize the structural damage of the irradiated samples and to in situ follow the dissolution reactions in corrosion experiments. The Raman spectra revealed significant depolymerization of the silicate network. The corrosion experiments were performed with both non-irradiated and irradiated glass sample in a silica-undersaturated, 0.5M NaHCO3 solution at 90°C (initial pH = 6.95) in a heated fluid cell that was mounted on an automated x-y-z stage of the Raman system. Timeand space-resolved, in situ confocal Raman

imaging of the reaction between the solution and the glass revealed an up to 4.5 times increased forward dissolution rate for the irradiated samples, demonstrating a strong impact of the structural damage on the dissolution behavior of the glass. This data suggests that the structural changes associated with self-irradiation of a HLW glass have to be considered when assessing the stability of nuclear glasses in a geological nuclear repository.

**Poster**

## Microparticle Production as Reference Materials for Particle Analysis Methods in Safeguards

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The International Atomic Energy Agency (IAEA) implements technical measures, or safeguards, in order to verify the compliance of member states their international legal obligations to use nuclear material and technology only for peaceful purposes. Predisposal and geological disposal of high-level radioactive waste and spent nuclear fuel, if declared as waste, is also subject to safeguards. One of the technical measures used are analytical measurements of samples taken during inspections of nuclear facilities. The application of this measure goes hand in hand with the development and advancement of analytical measurements and of reference materials for quality control purposes.

To this purpose, an aerosol-based particle production process was developed and established at Forschungszentrum Jülich. It is capable for the production of microparticles with consistent isotopic compositions and uranium contents intended as source material for certified reference materials for particle analysis methods applied in safeguards. A monodisperse particle size distribution as well as the single phase $U_3O_8$ structure was confirmed by EDX, mass spectrometry and µ-X-ray methods. Analysis performed on single uranium microparticles confirmed consistency of the uranium isotopic ratios in comparison to the initial precursor solutions.

In order to improve the homogeneity and particle handling, the particles are transferred into suspensions, for which the stability was investigated with respect to dissolution. Our results from dissolution experiments demonstrate that ethanol is a suitable medium for the storage of particles over a period of a few months. Using particles produced with the particle production setup to prepare particle suspensions by transferring collected particles into ethanol and subsequent distribution on several types of substrates, such as silicon wafers and cotton-swipes show consistent results. Additionally it was shown that the production of particle mixtures which are homogeneously distributed onto the substrates is feasible. The two step process developed at Forschungszentrum Juelich allows for a very flexible and time-saving preparation of various types of test samples suitable as reference materials for particle analysis methods applied in safeguards.

**Poster**

## Isotopic signature of non-crystalline U(IV) complexation with organic ligands

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Decades of U mining and processing left a legacy of contaminated aqueous systems, soils and sediments around the world. Strategies for remediation are commonly based on the reduction of the mobile U(VI) to more immobile U(IV), e.g. by stimulated microbial reduction.

However, U bioreduction results not only in the well-known uraninite ($UO_{2(s)}$) but also in non-crystalline U(IV) species associated with the cell envelope of metal- and sulfate-reducing bacteria. Non-crystalline U(IV) is not well characterized and significantly more labile than uraninite (Stylo et al., 2013). Hence, it is crucial to gain knowledge about it.

Various oxidants or complexation by organic ligands can cause dissolution or remobilization of non-crystalline U(IV). To minimize those processes at contaminated sites, amendments with organic substrates are often used to scavenge oxidants, which may enter into the subsurface through groundwater recharge.

Biotransformation of these organic compounds also generates metabolites such as organic acids with complexing capabilities. Accordingly, organic ligands regularly exist at contamination sites and presumably form soluble complexes with U(IV), as previously shown for EDTA and citrate (Luo & Gu, 2011).

Here, we examine in more detail the potential U isotope fractionation during the complexation and mobilization with varying ligand to U concentration ratios.

First, U(VI) (initial U concentration 400 µM) was reduced by *Shewanella oneidensis MR-1* in a phosphate-containing medium (WLP) under anoxic conditions to produce non-crystalline U(IV) (Stylo et al., 2013). In a first experiment, U was mobilized with EDTA (100 µM, 400 µM and 1000 µM). Aliquots in different time steps are analyzed for U concentration and U isotopic signature.

First results show that EDTA mobilizes non-crystalline U(IV). A larger ligand to U ratio results in faster and more extensive U mobilization. Further experiments with other ligands (e.g. citrate) will be performed in future.

References:

Luo, W., & Gu, B. (2011). Dissolution of uranium-bearing minerals and mobilization of uranium by organic ligands in a biologically reduced sediment. Environmental Science & Technology, 45(7), 2994-2999.

Stylo, M., Alessi, D. S., Shao, P. P., Lezama-Pacheco, J. S., Bargar, J. R., & Bernier-Latmani, R. (2013). Biogeochemical controls on the product of microbial U (VI) reduction. *Environmental Science & Technology*, *47*(21), 12351-12358.

Poster

## A Benchmark Experiment for Nuclear Waste Repositories

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Since the 1970th an official searching for a nuclear waste repository is underway. However, the amount of approved repositories for high grade nuclear waste is still small. The actual goal for a high grade nuclear waste repository in Germany is summarized by “Standortauswahlgesetz” [StandAG] and “Gesetzentwurf zur Fortschreibung des StandAG”.:

- The best possible repository needs to be used
- Depth of at least 150 m, better > 500 m should be used for a mined repository
- The repository needs to be qualified for at least one Million years (“Nachweiszeitraum”)
- The host rock should guarantee that no increase of radioactivity above natural level is expected outside the effective containment zone (“Einschlusswirksamer Gebirgsbereich”) – even after one Million years.

Here we propose a “Benchmark Experiment” which could be used to compare different repository sites and concepts (e.g. Grimsel, Mont-Terri, Äspö, Gorleben) in a quantitative manner against an independent approach. The “Benchmark Experiment” is designed as deep well repository. As deep wells are not foreseen as repositories at the moment, they can act as a benchmark without conflicts with the regulations by German parliament.

The concept is based on two major assumptions:

1. as a safety concept should include failure mechanisms based on time constant far beyond experimental times, a combination of different materials should be used to enhance the reliability of the system. In other geological deposition sites, natural multi-barrier-concepts are already implemented as minimum requirement (directive of European commission 2009/31/EC).
2. One should base safety concepts on long proven technologies. To our knowledge, the experience with abandonment of old mines is rather limited, whereas abandonment of wells (> 100 000) have a long lasting history.

While combining both ideas, one might obtain a “Benchmark Repository” with a high trustworthiness.

Multiple barriers with different properties and different safety-mechanisms (rheological, physical, chemical) will be combined in a systematic way, to use the advantages of different host, barrier and retardation systems, such as magmatic, clay dominated and salt formations in conjunction with an independent acting natural physical barrier.

12 wells should be drilled (5 as repositories and 7 for monitoring) down to ca. 3 000 m. Whereas the depth range between ca. 1 500 and 3000 m (within metamorphic rocks) would be the “Benchmark-Repository”.

The “Benchmark-Repository” might be a good solutions for other countries, which have not the luck of such a diverse geology as we have in Germany.

Talk

## Recovery of Metals from Metallurgical Waste Waters

**Klaus Philipp Sedlazeck[1], Daniel Vollprecht[1], Wolfgang Öfner[1], Peter Müller[2], Robert Mischitz[2], Gero Frisch[3], Michael Schlömann[3], Simone Schopf[3], Roland Pomberger[1]**

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Industrial waste waters often contain dissolved critical metals. A treatment of these metal-containing waters with zero valent iron (Fe(0)) yields a fixation of the critical metals through adsorption and (co-)precipitation reactions resulting in a secondary mineral waste consisting mainly of hydrous ferrous oxides (HFO). In the course of our research project “RECOMET 2.0 – Recovery of metals 2.0”, we focus on the recovery of the critical metals by physical, chemical, and/or biological methods.

The treatment of the industrial waste waters, i.e., the fixation of the dissolved critical metals is achieved by placing a Fe(0)-granule bed in a reactor and the critical metal containing water is pumped from the bottom through the reactor. The water flow causes a fluidization of the granule bed and an oxidation of the Fe(0)-granules surface, providing adsorption sites for the critical metals. Simultaneously, some of the critical metals are fixed through precipitation of discrete solid phases. Turbulences within the reactors abrades the HFO phase layer, resulting in a fresh and reactive Fe(0)-surface.

Prior to the treatment, hydrogeochemical modelling using PhreeqC is applied to predict the highest fixation rates by considering e.g. different pH regions, as well as the application of various chemicals. By changing geochemical properties within the reactors, the mineralogical and chemical composition of the solid output can be controlled and desired metals can, in the best case even selectively be removed from the waste water

According to the results of these models, the waters are treated and accrued sludges are separated from the suspension. Chemical analyses of the residual waste waters revealed removal rates of up to 99 % for Zn, Co, Mo, In and 95 % for W. So far, the critical metal content in the sludge had a maximum of 13 wt%.

For a successful recycling of the critical metals, an extraction from the separated slugde, or a passive enrichment by selective dissolution of undesired fractions that do not contain the valuable metals, is required. A detailed mineralogical and chemical characterization (XRD, EMPA, IC-MS, etc.) of the sludges is necessary to select appropriate leaching methods for a specific sample. It has been shown that Zn tends to form separate phases, whereas e.g., Co, W and Mo rather adsorb onto the Fe-bearing phases.

In this presentation, the general context of the project shall be presented, giving a special focus on the geochemical calculations, mineralogical/chemical characterization and the leaching methods.

**Talk**

## The role of accessory minerals on the stability of the bentonite backfill

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Bentonite clay is proposed as an effective barrier and buffer material suitable for sealing the gap between canister and the country bedrock in planned nuclear waste repository sites. Whereas there has been a strong focus on studying the stability of the dominant smectite component of the bentonite in aqueous solutions of varying composition, less consideration has been given to the role of the accessory mineral content. As industrial bentonites are mostly derived from the natural alteration of various types of volcanic rock, these clay deposits contain highly variable and complex with accessory mineral assemblages ranging between ca. 5 to 40 weight%. Published XRD quantifications show quartz to be the most common accessory mineral common to all bentonites. Other mineral phases that may occur (in general order of decreasing average abundance) are plagioclase, white mica, alkali feldspar, cristobalite, kaolinite, calcite, opal silica, dolomite, clinoptilolite, anatase, ilmenite, goethite, apatite, hematite, heulandite, gypsum, rutile, pyrite, barite, analcime and siderite. Amorphous phases have proved difficult to quantify, but is probably present in a number of ash-derived bentonites. Electron microscopy of the accessory fraction also reveals small quantities of zircon, monazite and crandallite to be present in some samples. The influence of accessory minerals on the stability of the bentonite material is discussed by considering possible detrimental effects, including i) loss of bentonite swelling due to redox reaction and/or substitution reactions (e.g. illitization), ii) possible corrosive reactions by acidification (e.g. sulfides, phosphates), iii) undesirable pressure effects due gas producing reactions (e.g. $SO_2$, $CO_2$), and iv) influence of organic compounds and microbial activity during water-mineral interactions open cavities. This review highlights the importance of the accessory minerals phases, which need to be considered when making the best choice of the bentonite material.

**Poster**

## Modelling the density-driven flow in deep aquifers up to the quasi-steady state using SPRING

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The objective of a repository for radioactive waste is to safely and permanently enclose radionuclides in deep geological formations. Therefore, comprehensive safety considerations have been incorporated in long-term safety analyses for repositories for radioactive waste. In early model calculations, the dispersion of contaminants from a repository up to near-surface groundwaters was examined based on the ultraconservative assumption of a freshwater groundwater system. To consider the density-driven flow in freshwater/brine systems in numerical models was not possible in early long-term safety analyses for large model domains over long simulation times due to limitations in computer speed and capacity. Therefore it was assumed - but not shown - that the transport of contaminants in brine systems is slowed down drastically compared to freshwater systems.

The aim of this study is to calculate the density-driven flow in deep aquifers with geological and hydrogeological data of a real site to study the transport behaviour of contaminants in freshwater/brine systems. To simulate groundwater flow, the code “Simulation of Processes in Groundwater” (SPRING) is used. SPRING is suited for multidimensional hydrogeological modelling of density-driven groundwater flow through porous media with salt concentrations up to saturation. Advection, diffusion and dispersion are regarded as transport processes.

Different two-dimensional models based on geological cross sections are set up using several parameter variations regarding hydrogeological parameters and hydraulic boundary conditions. This study shows a representative selection of several numerical simulations. The hydrogeological model has twelve different geological layers and considers several confined aquifers as potential migration paths for contaminants. The groundwater density depends on the salt concentration and is considered up to 1.250 kg/m³. Dirichlet boundary conditions for the salt concentration are used at the bottom of the model to represent the influence of salt layers.

As initial condition, the model domain is completely filled with freshwater and a hydrostatical pressure distribution is assumed due to the ground level elevation and averaged annual groundwater recharge rates at the surface. Due to the boundary conditions for the salt concentration, the density-driven flow is simulated over several million years until a quasi-steady state is reached. The results show the distribution of the salt concentration in the hydrogeological system and the approximation of a stable linear density gradient. The calculated density gradient is compared with field data, and differences between the flow velocities in freshwater and brine systems are shown.

# 9b,c) Geology of unconventional resources of critical raw materials

Poster

## Distribution and composition of REE minerals in polymetallic vein systems of the Harz Mountains, Germany

**Jonas Alles, Bernd Lehmann, Wilfried Liessmann, Thomas Schirmer**

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The Harz Mountains host several historically mined polymetallic hydrothermal vein systems of Mesozoic age, mainly hosted by Paleozoic clastic sediment sequences. Gangue carbonates of the former Bad Grund Pb-Zn-(Ag) mine in the Upper Harz Mountains are known for elevated REE contents up to >2000 ppm in bulk samples. This enrichment is due to the abundance of µm-sized REE minerals, mainly the fluorocarbonate synchysite ($CaREE(CO_3)_2F$), which can be best detected by scanning electron microscopy. Recently, we found further occurences of such REE mineral inclusions in 16 localities all over the Harz Mountains, mostly in hydrothermal calcite. This widespread occurence indicates a large and distinct, yet unidentified source of REE, participating in the different mineralizations of the Harz Mountains. Microprobe data from different localities in the Upper and Middle Harz Mountains show a remarkable variability in REE distribution in synchysite. The LREE/HREE ratio can be used as an indicator for fluid evolution and fluid flow paths, due to different REE complex stabilities in hydrothermal fluids. Slightly positive Eu anomalies in synchysite from the Upper Harz Mountains might indicate locally reducing fluid environments at temperatures >250 °C below the exposed hydrothermal system; strongly negative Eu anomalies in synchysite from St. Andreasberg, Middle Harz Mountains, likely indicate an interaction of the hydrothermal fluids with granites of the Late Variscan Brocken pluton.

Talk

## Trace element geochemistry of sphalerite in contrasting hydrothermal fluid systems: insights from LA-ICP-MS analysis, fluid inclusion microthermometry and sulfur isotope geochemistry

**Matthias Emanuel Bauer[1], Mathias Burisch[1], Jörg Ostendorf[1], Joachim Krause[2], Max Frenzel[1,2], Thomas Seifert[1], Jens Gutzmer[1,2]**

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A combined mineralogical and geochemical study was carried out on ore samples from polymetallic vein-type base metal mineralization of the Freiberg district (Germany). The hydrothermal veins comprise Permian Ag-Pb-Zn-Sb-Cu-Sn-In mineralization, and Cretaceous Ag-Pb-Zn-Ge-Ga-fluorite-barite mineralization. These temporally and genetically different vein types offer the unique opportunity to study the trace element geochemistry of sphalerite as a function of different hydrothermal environments. Fluid inclusion studies reveal that the Permian base metal mineralization formed predominantly due to boiling and cooling of a low-salinity (0 to 6 wt% NaCl eq.) fluid at c. 350 to 290 °C. This fluid is regarded to be of magmatic-hydrothermal origin. The Cretaceous mineralization formed, in contrast, by mixing of two brines (17 to 24 wt% $NaCl+CaCl_2$ eq.) with contrasting Na/(Na+Ca) ratios of 0.7 and 0.95 at about 120 °C. Inferred fluid sources and precipitation mechanisms are constrained by sulfur isotopic compositions of sulfides. The Permian ore stage is characterized by a narrow range of $\delta^{34}S$ from -2.3 ‰ to +0.9 ‰ VCDT, while the sulfides of the Cretaceous mineralization have a large scatter and significantly more negative $\delta^{34}S$ values (-30.9 ‰ to -5.5 ‰ VCDT). Contrasting fluid systems and ore-forming mechanisms are found to correspond to markedly different trace element systematics in sphalerite. The first generation of sphalerite (Sp Ia) in the Permian veins is significantly enriched in indium (geometric mean of 300 µg/g In, up to 1200 µg/g In) relative to Sp Ib (9 µg/g In) and the two Cretaceous sphalerite types (1 µg/g In for colloform Sp IIa and 3 µg/g In for coarse-grained Sp IIb). In contrast, Cretaceous Sp IIa has higher concentrations of germanium (geometric mean of 50 µg/g Ge, up to 1700 µg/g Ge), whereas Sp IIb contains the highest concentrations of gallium (90 µg/g Ga, up to 520 µg/g Ga). Temperature estimates ($T_{calc}$ (Sp Ia) = 358 ± 68 °C and $T_{calc}$ (Sp IIb) = 101 ± 63 °C), calculated from the concentrations of Ga, Ge, In, Mn and Fe in the sphalerite generations, are in very good agreement with the homogenization temperatures of fluid inclusions in crystalline sphalerite, thus confirming the recently defined GGIMFis geothermometer. The observed trace element trends in the sphalerite generations imply that In is specifically enriched in high-temperature, low to intermediate salinity fluids with a significant magmatic-hydrothermal fluid component, while Ge and Ga are more concentrated in low-temperature, high-salinity crustal fluids with no obvious magmatic-hydrothermal affiliation.

Talk

## Mineralogy and geochemistry of REE-Nb mineralization in the Gleibat Lafhouda and Twihinat carbonatites and associated Fe-oxides of the Ouled Dlim Massif in the Reguibat Shield (South Morocco)

**Rachid Benaouda, Dennis Krämer, Michael Bau**

*Jacobs University Bremen, Germany*

The recently discovered REE and Nb ore deposits in the Gleibat Lafhouda and Twihinat areas represent large REE-Nb mineralization associated with carbonatite and silica/Fe-oxides. The Gleibat Lafhouda intrusion is composed of Mg-carbonatite, which is crowned by massive Fe-oxides. The REE mineralization in this intrusion is mainly associated with the Fe-oxides and represented by monazite-(Ce). The occurrence of monazite as inclusions in apatite and along apatite cracks or as separated phases near apatite indicate its hydrothermal origin likely as a result of volatile- and iron-rich fluids that had interacted with the host rock. Preliminary microprobe analyses show that these monazites have very low Th contents (< 1%), which is very positive for a commercial extraction of the REE.

The main Nb mineral that formed in the Gleibat Lafhouda deposits is columbite, which is closely associated with iron oxides. This suggests that this deposit was formed by multiple stages of mineralizing fluids. Moreover, unlike the outcropping carbonatite the occurrence of monazite mineralization at depth within the carbonatite indicate a potential irregular ore distribution within the carbonatite body.

The Twihinat intrusion consists of Ca-carbonatite and massive silica/Fe-oxides. The carbonatite comprised of a white and a dark color, which is associated with REE and Nb mineralization suggesting the influence of metasomatizing fluids that percolated the through the parental carbonatite. The REE and Nb mineralization in this carbonatite is mainly represented by Ca-REE-F carbonate, synchysite-(Ce), parisite-(Ce), and pyrochlore.

The associated silica and Fe-oxides show similar ore mineralization as well as bastnaesite-(Ce) and monazite-(Ce) within both quartz and Fe-oxides. The transport of large amounts of REE and Nb, suggests that the transporting fluids were highly enriched in complexing ligands that allowed immobile elements like REE and HFSE to be readily transported in solution. These preliminary results clearly show that the two studied deposits are economically highly important and may deserve a world-class status.

Talk

## Geochemistry and mineralogy of selected mine tailings in Chile

**Khulan Berkh, Dieter Rammlmair, Malte Drobe**

*BGR, Germany*

Three tailing dumps in northern central-Chile (IV. Region) were geochemically and mineralogically studied for their economic potential and environmental impact.

According to bulk geochemistry of drill cores the first tailing exhibits the highest Co-content with a mean of 0.1 wt.% Co, whereas the second tailing bears elevated Cu-contents with an average of 0.5 wt.% Cu. The third one is enriched in several valuable metals including 0.03 wt.% Co, 0.7 wt.% Cu, 0.9 wt.% Zn and 0.1 wt.% Mo on average.

The mineralogy of the first tailing is simple. The most frequent mineral is pyrite followed by Fe-oxides. Minor phases consist of epidote, Fe-hydroxides and slags with different chemical composition. The main Co-bearing mineral is pyrite with Co-contents randomly differing from under detection limit to 3.2 wt.%. The second tailing presents the most variegated mineral assemblage dominated by Fe-oxides, ferro-hornblende, tourmaline, epidote, quartz, and Fe-hydroxides. The principal Cu-minerals are primary chalcopyrite and secondary malachite, pseudomalachite, libethenite, and connellite. The material in the third tailing is re-milled slag fragments. The fragments comprise a large number of phases that are either exsolved during cooling of the slag or agglomerated during deposition of the material. The phases are generally pyroxene, fayalite, Fe-oxides, albite, and quartz or glass with variable composition. Co, Cu, Zn and Mo occur as stoichiometric sulfides that form isolated large grains or as melt droplets in the slag fragments.

The recovery potential of the economic metals was studied. An enrichment of Co up to 0.3 wt.% and Cu up to 3.8 wt.% can be achieved by a density separation. Results of a solubility test of the metals in dilute sulfuric acid are highly variable depending on the mineralogy of the tailing.

The bulk content of heavy metals such as Hg, Cd, As, and Pb is low in all studied sites due to the absence of corresponding primary minerals. However, acid mine drainage (AMD) with a pH of 2.1 was generated at a weathering part of the first tailing, which was resulted by the excessive amount of pyrite. Co and Cu contents of the analyzed AMD were 103 and 136 mg/l respectively, whereas Hg, Cd, As, Zn and Pb contents remained under 2.4 mg/l. The other two tailings pose a low potential to generate AMD owing to high contents of carbonate (up to 20 wt.%) in the second tailing or the low abundance of sulfide minerals in the third tailing.

Talk

## Genesis of hydrothermal silver-antimony-sulphide veins of the Bräunsdorf sector of the Freiberg District, Germany

**Mathias Burisch[1], Anthea Hartmann[1], Wolfgang Bach[2], Patrick Krolop[1], Jens Gutzmer[1,3]**

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The peripheral regions of the Freiberg vein-type silver mining district comprise several sub districts of which Bräunsdorf was among the richest in terms of Ag grade. 114 t (ca. 3.9 million ounces) of Ag were historically produced from the Neue Hoffnung Gottes Mine near Bräunsdorf. Mining there exploited basically just one single hydrothermal vein, the Neuer Segen Gottes Stehender. The vein infill is marked by a polymetallic sulphide-quartz assemblage (known as kb stage across the Freiberg District) and abundant Ag-Sb-sulphide-carbonate-quartz mineralization, which is limited to the peripheral areas of the Freiberg District. Although Ag-Sb- and Sb-sulphides seem to be spatially and paragenetically closely related to each other, they typically do not occur together in the veins on the scale of meters. Instead, specific zones are dominated by Sb-sulphides without Ag or vice versa. Generally, the abundance of Ag-Sb-sulphides increases with depth.

To develop a sound genetic understanding of polymetallic sulphide-quartz and Ag-Sb-sulphide-carbonate-quartz mineralization in the Bräunsdorf sub district we conducted detailed textural analyses of ore and gangue minerals, fluid inclusion analyses, electron microprobe analyses and thermodynamic computations in order to characterize the ore fluids and ore-forming processes related to the Ag-Sb mineralization. The early-stage polymetallic-sulphide mineralization (stage 1) is related to fluids with low salinities (0.5 - 4 % eq. wt(NaCl)) and formed at temperatures above 300 °C. Microthermometric data related to minerals of the slightly younger Ag-Sb-sulphide assemblage (stage 2) show a range in salinity similar to ore stage 1, but have significantly lower homogenisation temperatures of 280-180 °C. Dissolution textures of previous ore stage 1 minerals and qualitative fluid constraints based on mineral chemistry imply that the composition of the ore fluid changed significantly from Cu-, Pb-, Zn- and As -rich fluids present during ore stage 1 to Ag-Sb-rich fluids prevailing during ore stage 2. Based on fluid inclusion data cooling can be regarded as the major ore-forming process. Reaction path model calculations for cooling of fluids with different initial pH values (5, 6 and 7) reproduce the observed mineral assemblages very well and predict spatial zonation of the Ag-Sb- and Sb-sulphide minerals that are in excellent agreement with field observations. We conclude that Ag-rich zones may well occur below Sb-rich zones in hydrothermal vein-type systems similar to those of the Freiberg District. This relationship may be of potential use for exploration targeting.

**Poster**

## Lithium-Cesium-Tantalum pegmatites in Zimbabwe and Western Australia, and the formation of Neo-Archean massive (Cs)-pollucite mineralisation

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Lithium-cesium-tantalum (LCT) pegmatites are important resources for rare metals. For Cs, only LCT pegmatites with massive mineralisations of the zeolite group mineral pollucite as at Bikita (Zimbabwe Craton) and Tanco (Superior Province Craton) are of commercial importance. Both deposits are hosted within greenstone belts and yielded Neo-Archean ages (~2.6 Ga). The Yilgarn and Pilbara cratons in Western Australia host many Meso- to Neo-Archean LCT pegmatites. For the evaluation of their Cs potential and of the genetic concepts of pollucite formation, the pegmatites from Wodgina, Londonderry, Mount Deans and Cattlin Creek were compared to the Bikita pollucite mineralisation [1]. LA-ICPMS U-Pb data from Ta-, Nb- and Sn-oxide minerals show that Bikita (2,616-2,625 Ma), Londonderry (2,640±9 Ma), Mount Deans (2,642±7 Ma) and Cattlin Creek (2,626±13 Ma) have the same age range and differ from Wodgina (2,858±13 Ma). The $^{40}Ar$-$^{39}Ar$ data from muscovite and lepidolite signalise that Bikita (2,317±15 Ma) and Wodgina (2,430±11 Ma) underwent later hydrothermal overprint, whereas Londonderry (2,609±6 Ma), Mount Deans (2,603±3 Ma) and Cattlin Creek (2,621±6 Ma) may have slowly cooled. A combination of Mineral Liberation Analysis by SEM and whole rock geochemistry demonstrates that the LCT pegmatites are characterised by similar mineral zonations except the massive pollucite zone at Bikita. This pollucite zone started to crystallise at the end of the main phase in the upper part of a thick subhorizontal pegmatite sheet. Rb, Li, Tl and F in all pegmatites increase continuously with Cs (up to 1 wt%) in the successive mineral zones along a magmatic fractionation trend, matching the classical concepts. There are no mineral zones with intermediate Cs concentration between this fractionation trend and the pollucite zone with 10-15 wt% Cs. This signals a distinct separate stage with massive Cs enrichment. After segregation of an immiscible melt with Cs-analcime composition in the upper portion of a pegmatite sheet, a further fluid-enhanced Cs enrichment towards a Na-pollucite compositions, via Cs+Al=Si+Na+OH substitution along the analcime-pollucite solid solution series may have taken place. Recently, a pollucite zone has been detected in LCT pegmatites located between the Londonderry and Mount Deans locations[2], proving the Cs potential in Western Australia.

### References

[1]Dittrich, T (2016). Meso- to Neoarchean Lithium-Cesium-Tantalum- (LCT-) Pegmatites (Western Australia, Zimbabwe) and a Genetic Model for the Formation of Massive Pollucite Mineralisations. Dissertation Faculty of Geosciences, Geoengineering and Mining at TU Freiberg/Saxony Germany, 341pp., **http://nbn-resolving.de/urn:nbn:de:bsz:105-qucosa-228968**

[2]Poineer Resources Ltd (2017). Mineral resource estimate for the Sinclair Cesium Project.

http://www.pioneerresources.com.au/project_pioneerdome.php

Poster

## What can we learn from mineral scalings in geothermal power plants?

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Basin brines used for geothermal heat extraction in the Oberrheingraben are mainly highly saline (TDS ≥ 100 g/L, Cl: >55 g/L). As a result, mineral scalings are likely to be formed within the power plants in the cause of heat extraction. Especially the high Cl-concentration can both be a nuisance and a promising hydrochemical feature. In the first case, Cl promotes pipe corrosion. In the second case, Cl-complexation mobilizes transition metals like Pb or Zn which explains their high dissolved concentration in many geothermal waters in the Oberrheingraben. Consequently, these waters are a promising future resource for the extraction of transition metals but also of many critical elements like Li, Sb, Mn, Ge, Be as they are enriched in the brine [1]. The development of selective and economic extraction methods would not only enable to farm metals but also help to control the formation of unwanted scalings that can disrupt the heat and power generation.

Our investigations on mineral scalings from the Oberrheingraben clearly indicate microbial induced reduction as major enrichment process leading to elemental precipitations (As, Sb) or sulfide formation (Cu, Au, Pb). Similar processes control the enrichment of Pb and Zn in Mississippi valley type ore deposits. In our study, for example, Cu is locally enriched in the scalings compared to the brine by a factor of $10^4$ - $10^6$. Other elements like Sr (enrichment factor (EF): 40), Ba (EF: 70) but also partly Pb (EF: 170) are enriched through carbonate precipitation, a process we assume to be also of importance for Li. Based on our results we propose to focus future research on controlled reduction e.g. through electrochemical reactions and carbonate precipitation as methods of choice for element harvesting from geothermal brines in the Oberrheingraben. One challenge that has to be tackled is to extract elements with economic potential without enriching potentially toxic or radioactive elements.

[1] Sanjuan, B., Millot, R., Innocent, C., Dezayes, C., Scheiber, J., Brach, M., 2016. Major geochemical characteristics of geothermal brines from the Upper Rhine Graben granitic basement with constraints on temperature and circulation. Chem. Geol. 428, 27–47.

Talk

## Potentials of unconventional Sn-W-In-resources – an ecological and socio-economic assessment

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A sustainable supply of raw materials is an essential requirement for the high-tech industry in Germany. By giving up mining of metallic ores in the early 1990s, Germany became entirely dependent on imports of metals of strategic economic importance associated with a high uncertainty of supply and little influence on the environmental conditions of global raw material production. Decreasing the supply risk of these strategic metals and reducing the ecological footprint of mining are the main objectives of the funding measure "$r^4$ – Innovative Technologies for Resource Efficiency – Research for the Provision of Raw Materials of Strategic Importance" initiated in 2015 by the German Federal Ministry of Education and Research. In this context, 16 $r^4$-projects are developing innovative exploration, mining, and processing technologies.

Within the scope of the integration and transfer project $r^4$-INTRA, we evaluate the technical $r^4$-R&D projects with regard to their ecological and socio-economic potentials. For this, we estimate the framework conditions for a successful implementation of the innovative technologies, developed within $r^4$, in the mining industry. Moreover, we review and summarize known but so far uneconomic ore deposits in Germany and worldwide that could become of economic interest by implementing the innovative mining and processing technologies of $r^4$. For the assessment of ecological potentials, we consider life cycle inventories of current raw material extraction in comparison to ecological benefits enabled by the new technologies.

In this contribution, we focus on potentials of unconventional Sn-W-In deposits in skarns that are formed by metasomatic processes. Skarn deposits can contribute to the broadening of the domestic and international raw material base and are on the scientific agenda of several $r^4$-projects. These polymetallic ores occur worldwide with significant deposits in the German Erzgebirge. However, due to their compositional complexity and the associated challenges in processing, most of the deposits outside China are up to now unexploited. Nevertheless, our results show that these global unconventional resources have the potential to replace ~52 % of the known tin resources in placer deposits whose exploitation causes significant damage to the environment. Major Sn-Skarn resources outside China are located in Australia and Germany. German resources could supply the domestic demand for tin for 13 years. Macroeconomic calculations show that tin mining in Germany would be economically feasible down to a tin grade of 0.3 wt% in the ores. Moreover, a sustainable, diversified international commodity market could significantly reduce the ecological footprint of tin mining.

Poster

## Petrogenetic investigations of sulfides from polymetallic skarn-type occurrences in the Ehrenfriedersdorf deposit, Germany: Coupled substitution processes of copper-indium in sphalerite

**Henrike Franke**[1], **Enrico Kallmeier**[2], **Claus Legler**[2], **Torsten Graupner**[1], **Ulrich Schwarz-Schampera**[1], **Katja Pursche**[1]

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The Erzgebirge represents the central part of the metamorphic basement of the Saxo-Thuringian zone of the Mid-European Variscides. It is located at the NW border of the crystalline Bohemian Massif. The metamorphic rock suite comprises a complex succession of greenschist to amphibolite facies mica schists, gneisses and metacarbonates with peak temperature and pressure values at eclogite facies conditions. Late Carboniferous to early Permian intrusions of late-collisional Variscian granites, subvolcanic dikes, microgranites, and lamprophyres caused metasomatic alteration of the metamorphic rock units and initiate the formation of different magmatic-hydrothermal tin and polymetallic sulfide greisen- and skarn-type deposits.

Samples for this study were provided by the BEAK Consultants GmbH and originate from the western area of the Ehrenfriedersdorf deposit characterized by the occurrence of Sn-bearing skarn-type rocks. Metasomatism of metacarbonatic and metapelitic rocks produced calc-silicate hornfels/skarn layers containing pyroxene, amphibole, mica, vesuvianite, calcite, fluorite and rarely malayaite. Layered Sn-rich polymetallic sulfide ores contain mineral assemblages of sphalerite, chalcopyrite, arsenopyrite, löllingite, cassiterite, pyrite, pyrrhotite and rarely scheelite. The samples were analyzed by optical microscopy, µ-EDXRF, XRD, EMPA, LA-ICP-MS to describe petrogenetic and chemical processes with special emphasis on the copper-indium distribution in sphalerite and chalcopyrite.

Medium- to fine-grained sphalerite crystals with up to 3.5 wt.% In and elevated Cu concentrations (up to 0.3 wt.%) show a homogeneous composition in back-scatter-electron images, without any mineral inclusions of roquesite or other indium-bearing mineral phases. However, detailed microscopic observations and textural evidences show that the sample suite contains late-stage roquesite ($CuInS_2$) in two different textures: (I) as orientated lamellae at fine to medium scale along the crystal planes of sphalerite but also (II) as aggregates with fine-grained irregular crystals associated with Fe-poor sphalerite with inclusions of secondary In-rich chalcopyrite. These evidences attest to diffusion induced segregation processes forming so-called chalcopyrite diseases [1] or diffusion-induced segregations [2]. These replacement reactions and exsolution-like phenomena in sphalerite indicate that the indium enrichment is related to the coupled substitution of copper and indium with zinc [3]. Our findings proof the mineralizing fluids to be saturated in indium and copper to the precipitation of roquesite in sphalerite.

This study contributes to the projects RoStraMet, HTMET (FKZ 033R131) of the BGR, and WISTAMERZ (FKZ 033R133) funded by the German government (BMBF).

[1] Barton PB and Bethke PM (1985) *American Mineralogist* 72, 451-467.

[2] Bente & Doering (1995) *Mineralogy and Petrology* 53: 285-305.

[3] Johan (1988) *Mineralogy and Petrology* 39, 211-229.

Talk

## Criticality - What makes a raw material critical?

**Max Frenzel**[1,2], **Jakob Kullik**[3], **Markus Reuter**[2], **Jens Gutzmer**[1,2]

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A key to the current debate on the supply security of mineral raw materials is the concept of 'criticality'. This presentation provides a brief review of the criticality concept, as well as the methodologies used in its assessment, including a critical evaluation of their validity. Furthermore, it discusses several risks present in global raw materials markets that are not captured by most criticality assessments. The key result is that current assessments of raw material criticality are fundamentally flawed in several ways. This is mostly due to a lack of adherence to risk theory, and highly limits their applicability. Many of the raw materials generally identified as critical may not be critical, meaning that new assessments are urgently required.

While these are important results for policy makers, it is not necessarily clear what their implications are for geoscientific research on critical element deposits, the topic of this session. Therefore, this question will briefly be explored in the second part of the presentation.

Talk

## Coal – A dispensable natural resource?

**Hartwig Friedrich Gielisch**

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At the end of 2018, Germany will have closed Germany's last two hard coal mines. However, closure does not imply the end of hard coal consumption. In 2017 Germany's power generation was based on 15.2 % on the use of hard coal. During the last years, public discussion in Germany on energy production and consumption has led to a prevailing opinion that the entire world is on its way to withdraw from the use of hard coal. This is, however, a fallacy.

Parallel to the abandonment of hard coal mining in the country, Germany developed to a significant coal importer being number 6 of the world's coal importers with some 45 Mt of hard coal in 2016. On the other hand, Germany still remains number 10 of coal-bearing countries with resources of 83 Gt of hard coal (www.whymap.org/BGR, 2016).

Today global players in coal mining and consumption are not located in Europe. While Europe produced 1.2 Gt of hard coal in 1980, Asia mined only 0.9 Gt of hard coal. In 2010, Europe's production shrunk to 0.6 Gt, while in Asia production increased to 4.7 Gt of hard coal. In addition, in the last 30 years world-wide hard coal production doubled from 4.1 Gt in 1980 to 8.1 Gt in 2010 due to the Asian coal boom. For example, in 1980 Indonesia had no significant coal production. Today, Indonesia is number 2 of the top sellers of hard coal directly behind Australia. In 2017, Indonesia produced 413 Mt and exported 292 Mt. India's steel industry cannot survive without Indonesian coking coal. Even China with a yearly hard coal production of 3.4 Gt in 2016 needs imports from Indonesia.

Environmental problems in China and India related to hard coal mining are known, but the enormous growth rate of the Indonesian hard coal mining led to environmental problems, which Asia had not seen before. In 2015, the Thai holiday island of Phuket was engulfed in a poisonous grey haze caused by illegal forest fires in Sumatra (1000 km South) and Kalimantan/Indonesia (2000 km South-East), which were fired in preparation for coal mining.

China, India and Indonesia signed the Paris climate agreement of the UNFCCC. This agreement allows China to emit 2.9 Gt and India to emit 2.3 Gt $CO_2$ until 2030. Destruction of the rainforest in Sumatra and Kalimantan by the Indonesian mining are, however, not part of the agreement.

**Poster**

## Germanium, gallium and indium concentration and distribution in sulfides of hydrothermal veins from the Black Forest ore district

**Sören Henning[1], Wolfgang Werner[2], Torsten Graupner[1]**

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The incorporation of high tech (HT) trace elements in sulfide minerals varies significantly between the different German ore districts depending on their genetic formation conditions such as metal source and fluid characteristics. During the creation of a database on HT trace element potentials for Pb-Zn-Cu deposits, 83 sulfide samples deriving from 19 occurrences of the Black Forest and the nearby Odenwald region were investigated. Mineralogical, textural and geochemical analysis were conducted by µ-EDXRF, LA-ICP-MS and EMPA.

Sphalerite occurs in the numerous hydrothermal fluorite-barite-quartz(-carbonate) veins of the Black Forest that are mainly located in paragneiss host rock and were formed by large-scale mixing of ascending high saline brines and meteoric water especially during the Late Jurassic and Neogene. Mineral distribution maps and mineral chemical spot analysis indicate varying iron contents in intensely zoned sphalerite of the "Schauinsland" deposit (median values: 2.15-7.45 wt.-%; range for individual spots: 0.11-11.57 wt.-%). The samples have high germanium (median 61-972 ppm) and elevated gallium concentrations (median 22-224 ppm). Germanium is incorporated in the sphalerite lattice by coupled substitution processes with monovalent silver cations for charge balance.

Sphalerite from „Gottesehre" deposit (St. Blasien) is characterized by low iron (<0.49 wt.-%), elevated gallium (156-475 ppm) and very low germanium (< 10 ppm) contents. At this location, the HT element gallium is positively correlated with antimony and monovalent cations (copper and silver) indicating an incorporation resulting from a coupled substitution process.

Sphalerite of the Münstertal region has moderate iron (2.24-5.91 wt.-%), relatively constant germanium (48-60 ppm) and elevated gallium (51-171 ppm) concentrations. Sphalerite of the "Kropbach" occurrence (Münstertal) mostly shows elevated iron (6-8 wt.-%) and very low trace element concentrations (Ge and Ga <20 ppm). However, high resolution EMPA mappings and BSE images indicate a younger oscillatory zoned low iron sphalerite (<0.71 wt.-%) that contains gallium (up to 362 ppm), copper (1200-3080 ppm), silver (up to 482 ppm) and antimony (up to 2556 ppm) especially enriched in sector zoning patterns.

In most sphalerites of the Black Forrest indium occurs restricted to single laser spots only (up to 1400 ppm) and forms the predominant HT element in the few measured chalcopyrite grains (10-200 ppm). Further research will be carried out focused on the relationship between trace element contents, regional host rocks and fluid characteristics of the Black Forest ore districts.

This study contributes to the project RoStraMet (BGR) and the project HTMET (FKZ 033R131) funded by the German government (BMBF).

Poster

## Influence of ore deposit type and regional geology on high tech trace element characteristics of Germany´s base metal ore districts – A new database on critical metals

**Sören Henning[1], Sven Birkenfeld[2], Henrike Franke[1], Torsten Graupner[1], Bernd Nawothnig[2], Katja Pursche[1]**

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High tech (HT) trace elements such as germanium, gallium and indium gain rising significance in the development of innovative technologies. A database was created to evaluate raw material potentials and HT element specializations of eleven historic base metal ore districts in Germany. Mineralogical, geochemical, and textural investigations on more than 100 Pb-Zn-Cu mineralizations were carried out using LA-ICP-MS, EMPA and µ-EDXRF.

The HT element database provides (i) the geochemical and mineralogical results, (ii) information on the regional infrastructure and environmental risks as well as on (iii) raw material-efficient processing of typical trace metal specialized ore types. Evaluation of combined data provides interactive maps of the potential of specific HT elements. Main objective of the project is the establishment of a fundamental basis for future exploration activities in the investigated areas and further in comparable EU regions.

Differences in the regional distribution of the above elements and a dependency on the genetic ore deposit type became apparent. The current results indicate elevated indium contents in sphalerite of the Sediment Hosted Massive Sulfide (SHMS) deposit “Rammelsberg” (287 ppm on average; Harz Mountains, Lower Saxony) and of the Skarn deposit “Ehrenfriedersdorf” (269 ppm, Ore Mountains, Saxony) with an absence of germanium and gallium. In contrast, germanium is the predominant HT element in collomorphic sphalerite of Carbonate-hosted lead-zinc ore deposits (MVT) in the districts of Aachen-Kelmis and “Wiesloch” in the Odenwald region (27 – 197 ppm).

Trace element concentrations in sulfides of hydrothermal vein deposits vary significantly depending on the host-rocks (metal source, tectonics) and fluid conditions (temperature, salinity). Clusters of ore deposits in the Ruhr area and the Black forest show an enrichment in germanium (37 – 229 ppm) whilst indium occurs locally in small grain domains (up to 4500 ppm) in some samples. However, sphalerite in deposits of the Ruhr district, Bergisches Land, Black Forest and Harz Mountains is characterized by moderate to high gallium contents (14 – 113 ppm).

Systematic investigations on trace element contents and distribution in sulfide ores indicate information about the source, transport and incorporation mechanisms of these critical elements in different mineralized systems.

This study contributes to the project RoStraMet of the BGR and the project HTMET (FKZ 033R131) funded by the German government (BMBF).

Talk

## Isotopes and trace elements incl. REY in formation waters from the North German Basin: Archives for long-term water-rock interaction and potential tools for exploration of mineral deposits under deep cover

**Dennis Kraemer[1], Marta Sośnicka[2], Volker Lüders[2], Michael Bau[1]**

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Exploration for ore deposits is becoming increasingly challenging, as many of the surficial (<1km) ore deposits have already been discovered. Hence, the mining industry has to target mineralization at ever greater depths in the future, also in greenfield exploration, in order to detect unknown ore deposits buried deeply in the underground. Tools and geochemical pathfinders for easy and especially cost-effective probing for covered mineralization are in high demand and will probably gain even more importance in years to come. Here, we report on formation waters from oil and gas production sites in the North German Basin and discuss their potential relation to mineral deposit formation. The North German Basin (NGB) features numerous oil and gas deposits which are currently exploited by a number of companies. Exploration and production drilling exposed hydrothermal mineralization in numerous areas all over the NGB. The formation waters are coproduced during oil and gas production and are highly saline brines representing deep groundwaters. The formation waters are mixtures of connate brines, meteoric brines and other fluids. Previous research indicates that formation waters from the North German Basin, especially from Rotliegend strata, may represent, at least in certain regions, original connate waters, i.e. basinal brines, which were capped and sealed by overlying Zechstein evaporite strata.

In this contribution we present trace element (including REY) as well as $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, δD and $\delta^{18}O$ isotope data for formation waters from North German oil and gas reservoirs and compare the results to geochemical data from adjacent hydrothermal mineralization and fluid inclusions hosted in base metal and fluorite-barite mineralization from nearby drill cores. Our preliminary results indicate certain similarities in the trace element and isotopic signatures of the formation waters to those found in hydrothermal minerals and fluid inclusions hosted within different types of mineralization. Hence, the formation waters and their geochemical signatures are potential archives for very long-term (>> 1 million years) water rock interaction, and their chemical signature might be used as a geochemical tool for exploration of mineral deposits under deep cover.

Talk

## Hydrothermal evolution of Sn deposits in the Erzgebirge – insights from fluid inclusions in ore and gangue minerals

**Maximilian Korges**[1], **Philipp Weis**[1], **Volker Lüders**[1], **Oscar Laurent**[2]

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Historic mines in the Erzgebirge are currently being reevaluated for their economic potential of critical and strategic metals. Even though some of these deposits are prominent and well-described examples in the scientific literature, the temporal and spatial evolution of the ore-forming systems are still debated.

This study focuses on two deposits, the Sn-Zn-In Hämmerlein and the Sn-W-Li Zinnwald mine. We analyzed fluid inclusions in gangue and ore minerals from skarn, greisen and vein samples using conventional and infrared-microthermometry and LA-ICP-MS. The analyzed fluid inclusion assemblages (FIA) are associated with the precipitation of the ore and give insights into the hydrological and chemical evolution of the fluid.The studied FIA show a wide spread of temperatures and salinities. Cassiterites in skarn minerals from Hämmerlein contain inclusions with homogenization temperatures of up to 525°C and salinities between 30 and 47 wt% NaCl eq., whereas cassiterites from veins and greisen show lower temperatures (300 - 400 °C) and low salinities varying from 2.5 to 6 wt% NaCl eq. The gangue minerals quartz and calcite mainly contain low temperature FIA with a high variability in salinity (max. 300°C and 2.5-9 wt% NaCl eq.) and rare low temperature, high salinity FIA (30 wt% NaCl q.). FIA in ore minerals from the veins of the Zinnwald deposit show similar temperatures, but in contrast to Hämmerlein can contain higher salinity brine inclusions associated to boiling, which has been inferred to be the controlling mechanism for Sn-W-vein mineralization at Zinnwald.

We further constrain the chemical composition of the ore-forming fluids by laser ablation-ICP-MS measurements of FIA in quartz and ore minerals. The presentation will show first results from the fluid inclusion study of the Hämmerlein deposit and compare them with the results from the Zinnwald deposit to constrain the differences and similarities between the ore-forming processes at these prominent Sn deposits in the Erzgebirge.

Poster

## $CO_2$-fluxing, cooling and fluid mixing as ore-forming mechanisms in antimoniferous vein-type mineralization of the Berga Antiform, Eastern-Thuringia, Germany

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The antimoniferous vein-mineralization in the Schleiz and Greiz area, eastern Thuringia, are bound to NE-SW striking Variscan fault zones along the margins of the Berga Antiform. Sb-Pb-Zn-sulfide-quartz ± carbonate minerals occur as massive veins, breccias or stockworks within Ordovician and Silurian metasedimentary units, Devonian metabasalts and metagranitoids. Mineralogical investigations of several Sb mines and hard rock quarries near Schleiz and Greiz, show that Zn-Fe-As-sulfide-quartz minerals (quartz I; ore stage I) are the oldest assemblage, which is followed by a Sb-Pb-Zn-sulfide-quartz ± carbonate assemblage (ore stage II and III) comprising e.g. stibnite, zinkenite and plagionite. This stage is followed by ore stage IV, which comprises late generations of sphalerite, galena and quartz III (ore-stage IV). Fluid inclusion studies on ore and gangue minerals of the subsequent ore stages show that primary fluid inclusion assemblages of ore-stage II (stibnite and quartz II) show variable vapor fractions and heterogeneous trapping of $CO_2$ at constant salinities. This indicates an influx of a buoyant pure $CO_2$ fluid into an aqueous fluid phase, rather than effervescence or boiling. The presented data demonstrates a unique example of $CO_2$-influx (from deeper levels) into an aqueous fracture fluid recognized in fluid inclusion. During ore-stage II a $H_2O$-$CO_2$-NaCl fluid, with eq. w(NaCl) of 1 to 2.7% at 220–226 °C prevails. In contrast, fluid inclusions in ore-stage III minerals (boulangerite) contain a homogeneously trapped $H_2O$-NaCl-$CaCl_2$ fluid, with eq. w(NaCl) up to 8.1% at temperatures ≥146 °C. Ore-stage IV minerals (sphalerite II, quartz III) contain a homogeneously trapped $H_2O$-NaCl-$CaCl_2$ fluid with eq. w(NaCl) of >20% and homogenization into the liquid phase at around 120 °C. Precipitation of Sb-minerals was most likely induced by the influx of $CO_2$, fluid cooling (quartz II – stibnite – boulangerite) and late stage mixing with a high salinity fluid resulting in the late precipitation of sphalerite II, galena and quartz III. We interpret these observations as an initially magmatic-hydrothermal fluid system, while in the late ore stages ingress of a highly saline, Pb-Zn-rich basement brine becomes more predominant, as the influence of the magmatic-hydrothermal fluids ceases.

Poster

## Mineralogy, geochemistry and fluid inclusion analyses of schist-hosted cassiterite-quartz-tourmaline-fluorite-sulfide veins of the Sn-In-polymetallic Hämmerlein project, Erzgebirge (Germany)

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The Erzgebirge-Krušné hory metallogenic province hosts numerous Sn-polymetallic mineralization. Greisen-, vein- and skarn- formation is most likely associated to late- and post-collisional Permo-Carboniferous acidic to basic shallow intrusions. The Pöhla-Hämmerlein Sn-In-polymetallic project is situated in the western Erzgebirge and comprises several skarn- and vein-type Sn mineralization, which overprint each other and therefore are clearly related to different ore stages.

One of the economically most relevant ore types is the historically termed “schist ore”- cassiterite-quartz veinlets are hosted by a two mica schist making up around 2.9 Mt of ore (indicated+inferred), with an average grade of 0.34 wt.% Sn. The schist ore Sn-mineralization-type appears as irregular trending veinlet mineralization, consisting of quartz, cassiterite, tourmaline, fluorite, and a minor amount of sulfides with thicknesses of up to 2 cm. The transition between host rock and veinlet is often marked by a small seam of hydrothermal altered schist (greisenization).

However, the schist-hosted cassiterite veinlets are yet poorly characterized with modern geochemical methods and consequently ore-forming processes are poorly constrained. To shed light on the genesis of the schist-hosted cassiterite veins of the Hämmerlein district, we carried out detailed field mapping and macroscopic description of this ore type, careful petrography, bulk geochemistry and microthermometry of ore-related fluid inclusion.

The bulk geochemistry (n=27; mineralized two mica schist) revealed high concentrations of incompatible elements such as Rb (160 - 1150 ppm, ø 520 ppm), Cs (7 - 330 ppm, ø 130 ppm), Li (40 - 370 ppm, ø 230 ppm), B (50 - 7660 ppm, ø 2720 ppm), F (0.21 wt.% - 2.0 wt.%, ø 0.96 wt.%), Sn (0.07 wt.% - 6.33 wt.%, ø 1.18 wt.%), and W (4 - 110 ppm, ø 30 ppm). This geochemical fingerprint indicates a genetic link between schist-hosted cassiterite veinlets and late-Variscan magmatic-hydrothermal activity associated with the Sn-W mineralization of the Erzgebirge. Fluid inclusion in cassiterite, quartz and fluorite show low salinities (below 6 % eq. w(NaCl)) and hydrothermal to pneumatolytic formation temperature ranging between 295 °C and 388 °C. In contrast, some fluid inclusions in fluorite show distinctively higher salinities of 12 - 19 % eq. w(NaCl) and lower $T_h$ (246 °C - 270 °C), which indicates that the fluid evolved towards higher salinities upon late stage cooling.

**Talk**

## REY and trace element chemistry of fluorite from post-Variscan hydrothermal veins in deeply covered Paleozoic units of the North German Basin

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Recent studies have presented new insights into the formation of mineralized fracture zones, including fluorite-barite and base metal sulfide mineralization, at depths of up to four kilometers within the North German Basin (NGB). In this context, we present a detailed petrographic and geochemical investigation of hydrothermal fluorite ($CaF_2$) in deeply covered Paleozoic sedimentary and volcanic units of the NGB. Samples from five E&P drill cores from the Altmark-Brandenburg Basin (ABB), two cores from the Lower Saxony Basin (LSB), a Flechtingen Calvörde Block (FCB) quarry and from the Biwender Vein (Harz) have been considered. The latter two were selected to uncover possible links between the hydrothermal mineralization in these areas and the NGB.

Carbonates, clastic sediments and volcanic units are crosscut by mm- to cm-wide ±quartz±carbonate±(anhydrite)-fluorite veins in Paleozoic units of the ABB. Fluorite is less abundant in samples from the LSB, where it predominantly occurs in Zechstein carbonates as pore filling cement or associated with base metal sulfides such as sphalerite. Complex growth zones, cyclical banding and/or redistribution patterns are evident in many samples and SEM-BSE and CL imagery revealed at least two generations of fluorite in samples from the ABB and the FCB, which can also be geochemically distinguished.

Overall, REY concentrations are comparatively low in fluorite from all investigated settings. The median sum of REY ranges from 0.3 to 176 ppm among the samples and concentrations of single REEs do not exceed 100 ppm. Europium anomalies are slightly negative or absent, indicating that the temperature of the hydrothermal fluid did not exceed 250 °C and fluid-rock interaction was likely controlled by complexation processes. Fluorites from the ABB and FCB show characteristic REY signatures that reflect two geochemically distinct fluorite generations—(I) with light SEM colors and relatively enriched LREE contents and (II) with darker SEM colors and comparatively depleted LREE contents and slightly higher HREE concentrations. A primary hydrothermal mineralization and a secondary geochemical remobilization signature is apparent in the Tb/La vs. Tb/Ca and La/Ho vs. Y/Ho discrimination diagrams. Our investigation suggests that the same trends can be the result of µ-scale growth zoning during a single continuous mineralizing event. This has implications for the interpretation of such trends and hence the inferred genetic evolution of fluorite that displays such geochemical patterns. The complex intergrowth of these fluorite generations stresses the need for detailed petrographic investigations in combination with high-resolution element analysis when geochemical data are collected and interpreted.

Talk

## HIGH-TECH METAL POTENTIAL OF SPHALERITE FROM EASTERN ALPINE LEAD-ZINC DEPOSITS

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Austria hosts numerous mineralizations with significant potential of the rare high-tech metals germanium, gallium, indium and cobalt, as indicated by chemical data of sulphide ore concentrates.

LA-ICP-MS data from sphalerite, which is a major host for some high-technology metals like Ga, Ge, In and Co are presented as part of a re-evaluation of three major types of base metal deposits in the Eastern Alps.

The three investigated ore types are:

(1) Carbonate-hosted "Alpine-type" or "Bleiberg-type" deposits hosted by Triassic limestones and dolomites of the Drau Range and the Northern Calcareous Alps are characterized by low Fe, high Cd (~2000 µg/g), Ge (200-400 µg/g) and Tl concentrations (~100 µg/g) in sphalerite and by the absence of Co (max. 1 µg/g), Cu, Ni. The Lafatsch deposit hosted in the Northern Calcareous Alps is a special case within this Group, hosting high amounts of Ag, but lower amounts in Mn, Ge, As and Tl compared to the other deposits of this type.

(2) In the Austroalpine nappe system, SEDEX-type deposits are known from the Graz Paleozoic and the Gurktal nappe. In-situ LA-ICP-MS measurements of sphalerite grains collected from five ancient mining sites and one exploration adit located in the Graz Paleozoic (Styria) reveal a large variation of trace element concentrations with median values of economic unimportant potential. SEDEX deposits hosted in Paleozoic units outside the Graz Paleozoic like Meiselding (Gurktal nappe), sphalerite carries up to 1900 µg/g In, 250 µg/g Ge, 65 µg/g Ga, 282 µg/g Co and 2.9 wt% Cd. In the Walchen deposit located in Koralm-Wölz nappe system is characterised by high In values (98 µg/g) but low values in Co (55 µg/g), Ga (1.53 µg/g) and Ge (0.07 µg/g). Sphalerite from the Leogang deposit hosted by upper Silurian-Middle Devonian dolomite showed the most elevated In concentrations in In (Md= 247 µg/g), the measured values for Co (128 µg/g) are in the range of the other investigated SEDEX deposits.

(3) Vein deposits of different genesis and age are widespread in the Eastern Alps. Pb-Zn-mineralization at Vellach-Metnitz in the Gurktal Nappe (Carinthia) unit shows vein-like NW-SE trending structures (WEBER, 1997). Metnitz, sphalerite carries up to 65 µg/g In, 924 µg/g Ge, 381µg/g Ga, 679 µg/g Co and 4380 µg/g Cd. High indium concentrations have been previously reported for the Zn-Cu-Pb veins of Koprein (Paleozoic of the Karawanken Range). Our LA-ICP-MS analyses of sphalerite show between 10 and 35 µg/g In.

Poster

## Contribution to the mineralogy and geochemistry of polymetallic vein-type mineralization in the western part of the Freiberg district (Erzgebirge, Germany)

**Stefan Schaefer[1,2], Thomas Seifert[1], Andreas Barth[2], Enrico Kallmeier[2], Tobias Petermann[1]**

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In the framework of the WISTAMERZ project "*Prognose wirtschaftsstrategischer Hochtechnologiemetalle am Beispiel des Erzgebirges"* funded by BMBF, approximately 280 stream sediment samples were taken from first and second order streams of a selected part of the Freiberg mining district in the *Erzgebirge/Kru□né hory* region. The samples were geochemically analyzed (ICP-MS/AES) and evaluated using various statistical methods and GIS. Based on the results, maps of anomalous element contents were developed. Thereby, regions could be localized which were suitable for rock sampling and related mineralogical comparison to gather further information regarding potential anomaly sources. In addition to geochemical analysis, reflected-light microscopy and SEM-EDS was used to identify local mineralization styles and the origin of high technology metals like In, Ge, Sb, Sn, and Ta.

The results of the stream sediment analysis combined with geochemical and mineralogical analyses of individual rock samples show that most of the anomalies could be assigned to known polymetallic Ag-base metal mineralization (e.g., Bräunsdorf ore field) including the elements Ag, As, Cu, Pb, Sn, and Zn. Besides geogenic sources these anomaly patterns are also considered to be reinforced by the intense anthropogenic overprint from smelters and processing plants of the historical mining district. Regarding the aim of the project to identify evidence of high technology metal occurrences no indication of element enrichment concerning Ge, Te, Ta, or Tl could be proved for the considered region.

A relatively large antimony-mercury anomaly (up to 60 ppm Sb, up to 1.5 ppm Hg in stream sediments) could be detected near the north-western edge of the investigation area, of which the central part is characterized by stibnite and cinnabar mineralization. In addition, in some samples from hydrothermal veins of the area partially increased contents of Au (up to 5.8 ppm) and Te (up to 2.5 ppm) could be detected. For the southern and northern extensions of this anomaly, deeper mineralizations are suspected.

Poster

## Ga-Al systematics of marine ferromanganese crusts and nodules reveal significant fractionation processes in aquatic environments

**Katharina Schier[1], Michael Bau[1], Thomas Kuhn[2], Katja Schmidt[1,2]**

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Gallium and aluminum show a coupled geochemical behavior in most natural systems and common rock types. The Ga/Al weight ratios of various basalt types, shales, average upper crust, and marine clay show very small variations with values between ~$0.2\times10^3$ and ~$0.41\times10^3$ (calculated from [1]). The geochemical behavior of the Ga-Al pair in the marine environment, however, is still poorly understood.

This study aims at gaining a first understanding of Ga-Al systematics in marine ferromanganese precipitates and reveals significant fractionation processes of the aforementioned geochemical partners.

Hydrogenetic ferromanganese crusts from the North Central Pacific show rather low Ga concentrations between 1.63 and 3.75 mg $kg^{-1}$ and a wide range of Ga/Al ratios ($0.24\times10^3$ up to $1.2\times10^3$). Hydrogenetic nodules from the same area are characterized by higher Ga contents (6.55 to 31.1 mg $kg^{-1}$) but similar Ga/Al ratios ($0.80\times10^3$ to $1.3\times10^3$ mg $kg^{-1}$) and diagenetic nodules from the Peru Basin show much higher Ga concentrations (4.08 up to 53.8 mg $kg^{-1}$) along with higher Ga/Al ratios ($0.48\times10^3$ up to $2.5\times10^3$). Surprisingly, mixed-type nodules from the Clarion-Clipperton-Fracture Zone (CCZ) do not fall on a mixing line between the hydrogenetic and the diagenetic precipitates, showing relatively invariable Ga concentrations with an average of 29.8 mg $kg^{-1}$ and Ga/Al ratios between $0.97\times10^3$ and $1.5\times10^3$, i.e. within the range of the diagenetic Peru Basin nodules but considerably less variable. Most likely, differences in pore water composition between the North Central Pacific and the Peru Basin and, therefore, differences in growth conditions are responsible for the variability of Ga-Al systematics.

Without exception, all hydrogenetic Fe-Mn crusts show lower Ga/Al ratios than ambient seawater (Ga/Al = $2.12\times10^3$ to $79.7\times10^3$; large range due to short marine residence times of Ga and Al), revealing preferential scavenging of Al relative to Ga. The lack of clear two-component mixing relationships between diagenetic Peru Basin nodules and mixed-type CCZ nodules may indicate significant differences between the Ga-Al distribution in pore waters at the CCZ and Peru Basin sites.

[1] Tarney et al. (1977) Philos. Trans. Royal Soc. A 300, 263-285; Gale et al. (2013) Geochem. Geophys. Geosyst. 14, 489-518; Le Roeux (1985) J. Petrol. 26, 1, 149-186; Lassiter et al. (2003) Chem. Geol. 202, 115-138; Rudnick & Gao (2003) Vol. 4, Treatise on Geochemistry 3, Elsevier, 1-64.

Talk

## Current Status of the German Polymetallic Sulphide Exploration in the Western Indian Ocean

**Ulrich Schwarz-Schampera, Ralf Freitag, Hendrik Müller**

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Germany has a long scientific track in marine research in the Indian Ocean. The first German scientific cruise took place in 1964, followed by several state-sponsored research cruises between 1983 and 1995 leading to the first finding of polymetallic sulphides in the Indian Ocean. The research included regional environmental investigations, particularly oceanographic and sedimentary base line studies. In 2010, BGR took the initiative for the preparation of an exploration claim for polymetallic sulphides, and prospecting started in 2011. After three years of resource-oriented and environmental studies, BGR applied for an exploration license which was signed with the International Seabed Authority in 2015.

The German exploration programme for polymetallic sulphides along the southern Central and the northern Southeast Indian Ridge spreading centres includes the collection of geological, geophysical, biological and environmental data for base line studies, as well as the testing and implementation of successful exploration programme strategies. The exploration cruises routinely conduct detailed rock and regional sediment sampling programmes, the measurements of oceanographic parameters (e.g., vertical and lateral mass transfers, water column analysis and bottom currents) and the analysis of faunal biodiversity and habitats. The comprehensive review of these recent studies and results from earlier German and other research cruises provides temporal information on the variations in the observed parameters.

The exploration for active and inactive polymetallic sulphides led to the identification of currently five areas of mineralization including seven active vents and 10 inactive sulphide fields. The ongoing programme aims at the localization of inactive seafloor massive sulphide occurrences, the estimation and measurement of the orebody dimensions, the analysis of metal concentrations and subsequently the identification of potentially economically feasible deposits. Additional objectives are the conceptual development of mining techniques and the design of an optimized and zero-waste metallurgical process.

Here we present the exploration concepts and results from our investigations after three years of exploration in the German claim for polymetallic sulphides in the Indian Ocean.

Talk

## Sources and pathways of ore-forming fluids in the Lower Saxony Basin, Germany

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Zechstein-2 carbonate-hosted hydrothermal Zn-Pb mineralization in the Lower Saxony Basin (LSB) that were locally drilled during gas exploration at depth between about 2700 and 3600 m share many similar features with MVT-type Zn-Pb deposits (Sośnicka and Lüders, 2018). Stratiform/stratabound ore formation in Ca2 reservoir rocks was related to mixing of ascending metal-bearing brines with hydrogen sulfide. The latter was derived by thermochemical sulfate reduction (TSR) in Ca2 gas reservoirs at paleo depths between 3300 and 4400 m. Similar near-surface stratabound Zn-Pb ores were historically mined from Ca1-carbonate in the surroundings of uplifted Carboniferous blocks in the southern part of the LSB. Although the source for $H_2S$ for ore formation is unambiguous, the source(s) of metals and pathways of metal-rich brines are not known. Metals may either be derived from deeper levels of the Paleozoic rock sequence or even from the crystalline basement.

The aim of this study is to trace migration pathways of metal-bearing fluids in various parts of the LSB. For this purpose we investigated elemental and metal abundances of fluid inclusions in fracture-filling quartz hosted by Upper Carboniferous strata and in gangue and ore minerals hosted by Zechstein carbonates (Ca1 and Ca2). We also studied trace element and metal concentrations as well as REE distribution in carbonates from Upper Carboniferous strata to determine origin of the carbonate-forming fluids.

Fluid inclusions in fracture-filling minerals hosted by Ca2 in Zechstein reservoirs show highly variable $H_2S$ contents. However, a significant decrease in $H_2S$ concentrations was observed in fluid inclusions hosted in fracture-filling minerals in drill cores that penetrated through abundant sulfide mineralization. Thus $H_2S$ was consumed by sulfide deposition. In areas where sulfide ores in drill cores are absent, $H_2S$ contents in reservoir gas remains very high (up to 35 mol%). However, fracture-filling quartz and carbonates hosted by Upper Carboniferous strata do not contain any $H_2S$-bearing fluid inclusions but locally host brine inclusions with elevated metal contents. These observations suggest that migration of metalliferous fluids and mixing with $H_2S$ from Ca2 gas pools across the LSB was tectonically controlled and appears to be related to stages of Cretaceous basin inversion.

References:

Sośnicka M. and Lüders V. (2018) Super-deep, TSR-controlled Phanerozoic MVT type Zn-Pb deposits hosted by Zechstein-2 gas reservoir carbonate (Ca2), Lower Saxony Basin, Germany. Chemical Geology, in press, https://doi.org/10.1016/j.chemgeo.2018.04.025

Poster

## Stability of the zinc sulphate hydroxides Gordaite, Bechererite and Namuwite: Phase relations and its applicability for recovery of metals from MSWI fly ashes

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MSWI (municipal solid waste incineration) fly ashes have high contents of Zn (about 4 wt%), Pb (about 1.5 wt%) and other volatile elements such as Cu, Hg, Cd, Cr, As and Ni. The treatment of the leachate wastewater produces high-voluminous sludges with a high content of Cl in addition to Zn and Pb, which means that these elements are lost for the circular economy. Our research question was therefore whether it is possible to recover these heavy metals by means of wastewater treatment.

Therefore, we studied the formation of Zn-minerals in the Na-K-Ca-Zn-$H_20$-$SO_4$-Cl system and the impact of salinity on the stability of the zinc sulphate hydroxides Gordaite ($NaZn_4(SO_4)(OH)_6Cl\cdot 6H_2O$), Bechererite ($Zn_4(SO_4)(OH)_6\cdot 6H_2O$) and Namuwite ($Zn_4(SO_4)(OH)_6\cdot 4H_2O$). For this propose, a solution with 2000 mg/L Zn was prepared. The concentration of $Cl^-$ and $SO4^{2-}$ was varied from 0 to > 70,000 mg/L $Cl^-$ and 5400 mg/L $SO4^{2-}$, respectively. The precipitation experiments showed, that the formation of the minerals strongly depends on the environmental conditions: Zincite (ZnO) precipitates at low salinity (0 mg/L $Cl^-$; 2900 mg/L $SO_4^{2-}$), Bechererite was only formed at medium salinity in the solution (7000 mg/L $Cl^-$; 3150 mg/L $SO_4^{2-}$). The stability of Gordaite requires high Cl-concentrations (70,000 mg/L $Cl^-$; 5400 mg/L $SO_4^{2-}$). By decreasing the Cl-concentration ≤ 7000 mg/L Gordaite becomes metastable and is converted into Namuwite. This shows that by treating the precipitates with pure water, $Na^+$ ions can be washed out of the structure of Gordaite. The coupled restructuring of the Gordaite due to substitution of $Cl^-$ by $OH^-$ leads to the formation of a low crystalline Namuwite.

Based on these results, we performed precipitation experiments with leachate wastewater from MSWI fly ash and worked out a two-step precipitation process. First (step 1), Zn bearing hydroxide sulphates, Laurionite (Pb(OH)Cl) and the salts Halite (NaCl) and Sylvite (KCl) precipitate. In step 2, washing the precipitates removes $Cl^-$ from the residues. Thus, Zn can be enriched in the residues by adjusting the experimental parameters. The recovery rates of Zn and Pb were ≥ 99%. At the same time, the Cl-concentration in the residue was reduced to 2,25% of the initial content. This concept helps to find new ways for MSW fly ash as a potential anthropogenic resource.

The research is funded by the Bavarian State Ministry of the Environment and Consumer Protection.

**Talk**

## Tin mobilization during melt generation

**Mathias Wolf[1], Rolf L. Romer[1], Leander Franz[2]**

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The partitioning of trace elements between restite and partial melt represents a first order control on the mineralization potential of a granitic intrusion by late or post-magmatic processes (fractionation, fluid exsolution). Partitioning of trace elements between melt and restite is controlled by (i) protolith chemistry and, thus, mineralogy), (ii) melting temperature, and (iii) mode of melt extraction.

Trace element analysis of high-temperature and low-temperature migmatites shows that muscovite-dehydration melting leads to enrichment of some trace elements (e.g. Sn, W, Sr, Ba, Zr) in the restitic domains. The stability of minerals as biotite, zircon, and/or monazite, which act as trace element sequestering phases in the restite, prevents partitioning of those elements into the melt. Trace element distribution in high-T migmatites (Bt-dehydration melting) is different from low-T, as the controlling phases are involved in melting reaction (e.g. biotite) or due to elevated solubility of host phases (e.g. monazite) in the melt. High-T melting is thus able to mobilize ore elements from the restite into the melt.

Retention of most trace elements in the restite during low-T melting leads to a residual enrichment. Under closed system conditions (i.e. low-T melt not extracted), ore element concentration of high-T melts is diluted by earlier melt batches. In contrast, if low-T melts are removed from the system before high-T melting, subsequent remelting of the restitic material produces small volumes of melt with relatively high trace element concentrations. The amount of melt that is produced during low- and high-T melting is controlled by the modal abundance of hydrous phases in the rock. Intensely weathered siliciclastic sediments contain high amounts of K and Al and are depleted in Ca and Na. Thermodynamic modeling shows that such protolith composition favors high modal amounts of muscovite and biotite during metamorphism. As a result, partial melting of such rocks leads to large amounts of melt during Ms-dehydration melting and relatively low melt volumes during Bt-dehydration melting. Additionally, such strongly weathered protoliths have slightly elevated ore element concentrations, which further enhance the overall ore element concentration during high-T melting.

Within a composite pluton with mineralization, extraction of multiple melt batches that were formed at different temperatures (muscovite vs. biotite melting) is reflected by large volume of early granites that are barren and by small volume of late granites that are mineralized.

# 9d) Magmatic ore deposits

Talk

## The source of metals in the recent polymetallic sea-floor massive sulfide mineralization at the Kolumbo arc-volcano, Greece

**Qasid Ahmad**[1], **Clifford G.C. Patten**[1], **Jochen Kolb**[1], **Stephanos P. Kilias**[2], **Yann Lahaye**[3], **Iain Pitcairn**[4]

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Seafloor massive sulfide (SMS) deposits which represent modern equivalents of on-land volcanogenic massive sulfide (VMS) deposits are one of the main target settings to secure sustainable access to raw materials in metal resources in the submarine environment. The Kolumbo shallow-submarine arc-volcano (Greece) hosts an active Au-rich SMS mineralization associated with thinned continental margin volcanism in the 5 Ma-to-present active Hellenic Volcanic Arc (Kilias et al., 2013). Active and inactive hydrothermal chimneys of the Kolumbo SMS are uniquely enriched in elements with an epithermal geochemical association (Au, As, Sb, Hg, Ag, Tl, Ag) and may represent a hybrid style of epithermal VMS-mineralization (Kilias et al., 2013). Previous studies demonstrate that mantle volatiles play an important role in the Kolumbo SMS deposit (Kilias et al., 2017, and references therein) but it is still unclear which metals were mainly transported by magmatic fluids and which were leached from host rocks. To better constrain the sources of metals, petrographic investigations of a massive sulfide-sulfate spire were performed and combined with in-situ LA-(MC-)ICP-MS analyses in order to precisely determine the trace metal contents and the isotope signature of sulfide phases. Primary formed colloform banded pyrite with fine interlayers of galena and/or Sb-Pb-sulfosalts and porous zones which were originally filled by galena indicate variations in fluid chemistry and/or physicochemical fluid-properties. Furthermore, the occurrence of alternating pyrite and marcasite sequences, sphalerite-replacement by chalcopyrite, pyrite-replacement by barite, and late stage barite associated with Sb-Pb-sulfosalts indicate multiple changes in fluid conditions due the episodic nature of the Kolumbo hydrothermal vent system. Lead and sulfur isotopic variations suggest that the fluids at Kolumbo are not dominated only by magmatic degassing but that hydrothermal fluids related to deep hydrothermal circulation are also present, which is in agreement with aforementioned petrographic observations. Combined with trace element analyses it is possible to decipher the sources of metal(loid)s at the polymetallic SMS mineralization of Kolumbo.

References:

Kilias, Stephanos P.; Nomikou, Paraskevi; Papanikolaou, Dimitrios; Polymenakou, Paraskevi N.; Godelitsas, Athanasios; Argyraki, Ariadne et al. (2013): New insights into hydrothermal vent processes in the unique shallow-submarine arc-volcano, Kolumbo (Santorini), Greece. In: Scientific Reports 3, S. 2421.

Kilias, S. P., Zygouri, E., Nomikou, P., Chrysafeni, M., Ivarsson, M., Chi Fru, E., El Albani, A., Zack, T., Pitcairn, I., Argyraki, A., Gousgouni, M., Polymenakou, P., Carey, S. (2017): Metal resource potential of modern sea-floor massive sulfides at Kolumbo shallow-submarine arc-volcano (Santorini), Greece. In: Goldschmidt Abstracts.

Talk

## Mobilization of platinum-group elements and the neoformation of platinum-group minerals under supergene conditions

**Thomas Aiglsperger**[1], **Joaquín Proenza**[2], **Francisco Longo**[3]

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Platinum-group minerals (PGM) are a group of minerals for which at least one of the six platinum-group elements (PGE) (i.e. Os, Ir, Ru, Rh, Pt, Pd) is essential to the mineral. In general PGM occur as micrometric inclusions in magmatic host rocks which has led to the over-all assumption that PGM are hypogene in origin, including PGM found in surface environments such as placer deposits (e.g. Hattori and Cabri 1992). However, an alternative view on the origin of some PGM found in supergene environments suggests that PGM can effectively grow in supergene settings from low-T fluids (e.g. Augustithis 1965). In recent years, several laboratory and few field studies have proven that e.g. Pt is mobile and bioavailable under certain surface conditions leading to bio-neoformation of Pt nanoclusters in the presence of microorganisms (e.g. Reith et al., 2016).

Since almost a decade our research group investigates large, oxidized deposits associated with near surface modification of ophiolitic ultramafic rocks (i.e. Ni-laterites) for their potential as future unconventional PGE ore deposits. During this study innovative hydroseparation technique for heavy-mineral concentration was used and several PGM with delicate morphological features such as botryoidal textures or spherical nanoclusters were discovered. Textural, chemical as well as crystallographic evidence obtained via SEM, EMP, Raman spectroscopy and through-the-substrate µ-XRD analysis points to a multistage formation of PGM found in investigated Ni-laterites: (i) primary PGM formation at magmatic stage; (ii) transformation to highly porous secondary Os-Ru PGM during serpentinization; (iii) neoformation of Ir-Fe-Ni-(Pt) mineral phases during early stages of lateritization; (iv) neoformation of Pt-(Ir) mineral phases within the critical zone close to the surface of the profile resulting in nugget shaped accumulation of rounded grains during late stages of lateritization.

This contribution aims to give a good example of how PGE are mobilized in low-temperature environments with subsequent in-situ PGM neoformation under surface conditions by explaining the case of Ni-laterites.

Augusthitis SS (1965) Mineralogical and geochemical studies of the platiniferous dunite – birbirite – pyroxenite complex of Yubdo, Birbir, W. Ethiopia. Chemie der Erde, 24:159-165.

Hattori K, Cabri LJ (1992) Origin of Platinum-Group-Mineral Nuggets inferred from an Osmium-Isotope Study. Can Min 30:289-301.

Reith, F., Zammit, C.M., Shar, S.S., Etschmann, B., Bottrill, R., Southam, G., Ta, C., Kilburn, M., Oberthür, T.; Ball, A.S., Brugger, J. (2016) Biological role in the transformation of platinum-group-mineral grains. Nat Geosci, 9, 294–298.

Talk

## An experimental study on pyrrhotite, galena, sphalerite and chalkopyrite stability in peralkaline iron-rich melts: the influence on melt evolution and trace element partitioning

**Björn Bethge, Michael Marks, Marcus Nowak**

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We present phase equilibrium experiments using a peralkaline Fe-rich (~12 wt.%) phonolitic glass doped with F and Cl that resembles a potential parental melt composition of the peralkaline Ilímaussaq plutonic complex/South Greenland (Marks & Markl 2003, Giehl et al. 2013; 2014). To investigate sulfide stability in such compositions, this glas was doped with about 2000 µg/g Ni, Co and Cu and four different sulfides (FeS, PbS, ZnS and $CuFeS_2$) were added to adjust to a bulk sulfur content of 0,5 to 1,0 wt.%.

The nominally dry experiments where performed in gold-graphite capsules using hydrothermal rapid-quench cold seal pressure vessels at 100 MPa, 950 and 850°C and FMQ-1 to FMQ-3. This $T$ interval was chosen to investigate the early magmatic mineral assemblages coexisting with residual melt. After quenching, titanoferous magnetite, fayalitic olivine, alkali feldspar, fluorite, various sulfide phases, Fe-Ni-Co alloy and native lead were identified together with residual glass. Except for the sulfides, Fe-Ni-Co alloy, native Pb, and fluorite instead of hedenbergite, this mineral assemblage resembles the one found by Giehl et al. (2014) in 850 °C experiments.

The identified sulfide phases can be divided into quenched sulfide melt at 950 °C and crystalline sulfide phases at 850 °C. The quenched sulfide melts show a round blob shape and an internal microcrystalline and partially inhomogeneous structure. The galena-doped experiments show quenched sulfide melts with a porous core constisting of native Pb surrounded by a (Fe,Pb)S quenched phase. In addition, quenched Fe and Pb sulfide melts occur together with Fe-Ni-Co alloy. At 850 °C porous galena and pyrrhotite coexist with some melt residues surrounded by a (Fe,Pb)S phase. In pyrrhotite-doped experiments crystalline pyrrhotites show a cation/anion ratio of 0,98 – 0,92, covering a similar but smaller range compared to pyrrhotite in natural Ilímaussaq rocks (Babiel et al. in press). The experiments doped with sphalerite and chalcopyrite are currently under investigation.

Sulfur concentration in the residual glasses vary from about 200 µg/g in galena-doped experiments to about 550 µg/g in sphalerite-doped experiments. Contents of Zn and Pb in the residual glasses reach 8100 and 2000 µg/g , respectively. The maxium Co content is about 380 µg/g, whereas Cu and Ni contents barely exceed the electron microprobe (EMP) detection limits of around 105 and 90 µg/g, respectively. Further analytical difficulties with EMP analyses remain because of cracks, surface roughness, porosity and/or very small sulfides phases.

Talk

## Magmatic formation and hydrothermal overprint of the Vergenoeg fluorite deposit, South Africa

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Situated in the Paleoproterozoic Bushveld Complex, the Vergenoeg F-Fe-REE deposit is the largest fluorite deposit worldwide. Despite the economic importance of the deposit, its petrogenesis is poorly understood. Hydrothermal ore formation through fluids released from fractionated Bushveld granites or from carbonatite-related alkaline rocks has been postulated (1, 2, 3). In another model ore formation is ascribed to separation of an immiscible Fe-rich magma from a parental felsic magma (4). The deposit consists of three rock units, a fayalite, magnetite-fayalite and magnetite-fluorite unit from bottom to top.

We have detected a gabbroic xenolith in the fayalite unit that records the magmatic evolution of the deposit and documents its petrogenetic link to the Upper Zone of the Bushveld Complex.

The gabbro is dominated by oscillatory-zoned magnesio-hastingsite phenocrysts (XMg: 0.95-0.86), comprising inclusions of plagioclase ($An_{45-51}$), F-apatite and magnetite. The composition of the amphibole resembles those in gabbros of the Upper Zone of the Bushveld Complex (5), suggesting a petrogenetic link. High fluorine contents (1.9-2.5 wt.% F) document magnesio-hastingsite crystallization from a fluorine-rich melt. Rimward decreasing XMg and fluorine of the amphiboles document subsequent differentiation of the melt. Moderately REE-enriched magnesio-hastingsite displays a pronounced negative Eu anomaly, consistent with its igneous formation following plagioclase fractionation.

Magnesio-hastingsite is surrounded by a fine-grained matrix of albite, K-feldspar, quartz, fluorite, hastingsite, F-apatite and allanite that formed through hydrothermal replacement of the igneous magnesio-hastingsite-plagioclase-F-apatite-magnetite assemblage. Amphibole overgrowths on the phenocrysts are Fe-rich (XMg: 0.45-0.21), contain significant chlorine (up to 1.2 wt.% Cl; only 0.4-0.0 wt.% F) and show significant REE-enrichment. The change of the halogene component of igneous and secondary amphibole records the incipient growth of fluorite, which is enclosed in amphibole margins and is also present in the hydrothermally-formed matrix. Albitization of magmatic plagioclase was associated by fluorite growth along fractures of plagioclase.

The amphiboles document formation of the gabbro from a F-rich melt that originated from the Upper Zone of the Bushveld Complex. During subsequent fractionation the melt became Fe-, REE- and F-richer and fayalite of the fayalite unit cumulated. The following hydrothermal overprint caused F- and REE-enrichment and is recorded by the formation of the fluorite-bearing secondary assemblage in the gabbro.

(1) Borrok et al. (1998) Economic Geology, 93, 564-586

(2) Goff et al. (2004). Mineralogy & Petrology, 80, 173-199.

(3) Graupner et al. (2015). Ore Geology Reviews, 64, 583-601.

(4) Crocker (1985) Economic Geology, 80, 1181-2000.

(5) Hayes et al. (2017). AGU meeting 2017.

**Poster**

## Constrains on the parental magma of the Upper and Upper Main Zone of the Bushveld Complex

**Lennart Alexander Fischer[1,2], Bernard Charlier[3], Olivier Namur[4], Francois Holtz[1]**

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The Bushveld Complex in South Africa is the largest layered intrusion on Earth. Its Upper Zone hosts several economically important magnetite (enriched in vanadium) and nelsonite layers. The Upper and Upper Main Zone are traditionally combined and considered as a single unit with the Pyroxenite Marker at its base. In recent years it has however been shown that the Upper and Upper Main Zone was formed by multiple magmatic injections (Ashwal et al., 2005; Yuan et al., 2017).

This study experimentally investigates the phase equilibria of several proposed and new calculated possible parental magmas of the UUMZ, ranging from basaltic to andesitic compositions. Experiments are designed to simulate the simultaneous crystallization of the first cumulate minerals above the Pyroxenite Marker (plagioclase, orthopyroxene and clinopyroxene). This assemblage is interpreted to represent the first cumulates of the Upper and Upper Main Zone. Crystallization experiments were conducted in an Internally Heated Pressure Vessel at temperatures between 1080°C and 1140°C and a pressure of 2 kbar.

In contrast to previously proposed basaltic compositions, the experimental results indicate that the parental magma to the Upper and Upper Main Zone of the Bushveld complex must be enriched in silica. The crystallization experiments revealed that the mineral assemblage of plagioclase + low-Ca-pyroxene + clinopyroxene cannot be reproduced at realistic temperatures from a basaltic melt, but that this assemblage can start to crystallize within a narrow temperature interval (1080°C - 1120°C) from an andesitic melt. There is also evidence from mineral compositions, that small amounts of water (< 1wt%) were present in the Upper and Upper Main Zone parental magma.

*Ashwal, L.D., Webb, S.J. & Knoper, M.W. (2005). Magmatic stratigraphy in the Bushveld Northern Lobe: Continuous geophysical and mineralogical data from the 2950 m Bellevue drillcore*

*Yuan, Q., Namur, O., Fischer, L.A., Roberts, R.J., Lü, X. & Charlier, B. (2017). Pulses of plagioclase-laden magmas and stratigraphic evolution in the Upper Zone of the Bushveld Complex, South Africa. Journal of Petrology, 58(8), 1619-1643.*

**Talk**

## Insights into geology and genesis of the Angstberg intrusive body and its associated Ni-Cu-(PGE) sulfide mineralization (Lusatian Block, Northern Bohemian Massif, Germany)

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The Angstberg intrusive body and its associated Ni-Cu-(PGE) sulfide mineralization is located in the Upper Lusatian Highlands about 4 km W of Steinigtwolmsdorf. The 325 x 75 m Angstberg intrusive body exhibits an asymmetric rhomboid-like shape in plan view and comprises olivine-gabbronorite, olivine-gabbro, gabbrodiorite and olivine-amphibole-gabbro lithologies. It belongs to a complex of Devonian (~ 380-370 Ma) small-scaled dike- to stock-like ultramafic to mafic intrusions intruded the Cadomian granodiorites of the Lusatian Block (Northern Bohemian Massif). Geometry, petrography and geochemistry suggest that the Angstberg intrusive body represents a sub-vertical magma conduit that was flowed through by several pulses of basaltic magma.

The magmatic Ni-Cu-(PGE) sulfide mineralization was discovered during dimension stone mining operations in 1971. Disseminated sulfides (globular sulfides and interstitial sulfide blebs) hosted by olivine-amphibole-gabbro and olivine-gabbronorite are the predominant mineralization style. Sulfide contents in the olivine-amphibole-gabbro and olivine-gabbronorite vary between 1-30 vol.% and 1-5 vol.%, respectively. Nickel, Cu and PGE tenors (concentration in 100% sulfide) vary between 4-9 wt.% Ni, 2-6 wt.% Cu and 0.7-1.8 ppm PGE (Total). Additionally, some semi-massive sulfides associated with a sulfide-matrix breccia, hosted by the granodioritic country rock directly below the northern footwall contact of the conduit, were exposed during mining operations in the 1990`s. Sulfide contents of these ores vary between 15-70 vol.% with tenors of 4-6 wt.% Ni, about 1 wt.% Cu and 0.1-0.9 ppm PGE (Total). Light-microscopy and SEM reveal that the magmatic sulfides in the different ore types are characterized by a predominance of pyrrhotite over pentlandite and chalcopyrite. The sulfides are associated with abundant Fe-Ti oxides as well as accessory PGE-, Bi-, Ag- and Au-phases (< 1-20 µm). Nickel-rich bismuthotellurides of the melonite-merenskyite solid solution series are the most common PGMs. Froodite and sperrylite occur in subordinate amounts.

The abundance of disseminated sulfides (1-30 vol.%), their grain sizes (up to 4 cm) as well as the high Ni tenors (4-9 wt.%) suggest that the sulfides associated with the olivine-amphibole-gabbro and olivine-gabbronorite were not formed by in-situ sulfide saturation and segregation from the basaltic parental magmas. Sulfide saturation and formation of immiscible sulfide liquid probably took place in deeper parts of the conduit system, e.g. within staging chambers, and was likely triggered by olivine fractional crystallization and assimilation of siliceous granodioritic country rock. Sulfides were likely entrained in an olivine-laden crystal mush to upper levels of the conduit system and were probably deposited due to changes of the conduit`s geometry.

**Poster**

## How do platinum-group elements occur in sulfides – as solid solution or as nanometer-sized inclusions?

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The Bushveld Complex in South Africa hosts the world's largest resources of platinum-group elements (PGE), which occur both as discrete platinum-group minerals (PGM), and hosted by sulphides (e.g. Junge et al., 2014). High resolution maps were prepared using a transmission electron microscope (TEM) in order to reveal the distribution of PGE in sulphides on a nanometer-scale. Electron transparent foils (5 x 10 x 0.15 µm) were prepared using the FIB technique, sputtering material from the sample with Ga-ions accelerated to 30 keV. The foils were prepared from pentlandite of the UG-2 chromitite (Karee Mine) and of the Platreef (Sandsloot). In both cases, discrete PGM like cooperite/braggite, Pt-Fe alloys, laurite and PGE-bismuthotellurides (~1 to 100 µm) were detected by ore microscopy and subsequently analysed by EPMA. The TEM study confirmed the presence of µm-sized PGM and showed additionally that PGE occur in pentlandite (i) as nanometer-sized-inclusions of PGM, and (ii) within the pentlandite lattice substituting for Ni and/or Fe.

Patchily distributions in pentlandite comprise concentrations of Rh and Ir in the form of small (10 to 100 nm) specks. An EDX line profile across one single patch demonstrates that these patches represent an enrichment of Rh and Ir and simultaneous depletion of Fe and Ni.

In pentlandite grains from the UG-2 with high concentrations of Rh (up to 12.5 wt%) and Pd (up to 0.05 wt%), Rh and also Ir form an ordered arrangement within the crystal lattice in the form of orientated nanometer-thick lamellae. EDX analyses demonstrate that these structures represent alternating Rh-/Ir-rich lamellae and Ni- and Fe-poor zones. These periodic structures form a superlattice, i.e. an ordered arrangement within a crystal.

A Pt-(Fe,Cu) alloy with a slightly distorted diffraction pattern indicated by smeared out Bragg reflections visible at the higher order reflections. The coalescence of "embryos" or precursors forming crystals with minute misorientations at the interfaces causes a slightly disturbed diffraction pattern (e.g., Penn and Banfield 1998).

PGE in the UG-2 and in the Platreef are present as a continuum of discrete PGM to nPGM, substituting for Ni and/or Fe in the crystal lattice of pentlandite, and at extremely high concentrations, PGE may form superlattice structures. Platinum-group minerals can be formed by coalesces of pre-existing crystals.

**References:**

Junge, M., Oberthür, T., Melcher, F. (2014), Economic Geology, 109, 795-810.

Penn, R., Banfield, J. (1998), Science 281, 696–971.

Poster

## Element partitioning at the magmatic-hydrothermal transition in a shallow plutonic system

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Quartz crystals from miarolitic cavities in the Torres del Paine igneous complex, Chile, contain inclusions that document the fluid-related processes during the complete late-stage magmatic-hydrothermal evolution of the pluton. Inclusion petrography and microthermometry combined with growth textures of Quartz crystals identified by variable pressure, secondary electron (VPSE) imaging and oxygen isotopic compositions are used to reconstruct the late magmatic-hydrothermal history of the pluton with focus on the partitioning behaviour of elements between residual water-saturated melt and aqueous fluid. This stage is decisive for the mass transfer of elements between geological reservoirs and also central to ore deposit forming processes.

Coeval silicate melt inclusions and magmatic aqueous fluid inclusions were analysed by individual inclusion LA-ICP-MS [1] to calculate partition coefficients for a set of 42 elements from Li to U.

This broad data set can be divided into groups of elements according to their fluid or melt affinity. Fluid mobile elements such as e.g. Zn, Ag, Pb, or Mn are characterised by fluid-melt partition coefficients ($K_D$s) >50. These elements are likely to be enriched in magma-derived fluids and are therefore expected to be dominant in magmatic-hydrothermal ore deposits. Arsenic, Cs, Mo, and Sr are among a group of moderately fluid mobile elements with $K_D$s in the range of 5-50, while the group of least mobile elements (e.g. Zr, Th, Nb, and Ce) exhibits $K_D$s <0.1.

A first evaluation of the data set indicates a general agreement with previously published data [2], but we observed more extreme $K_D$ values for some elements (e.g. Zn, Pb, Sn, and Zr, Nb), even though internal analytical variations are small. This observation might indicate a pressure effect on element partitioning, as the system studied here represents very shallow emplacement conditions.

[1] Pettke et al. (2012) *Ore Geol Rev* **44**, 10-38.

[2] Zajacz et al. (2008) *Geochim Cosmochim Ac* 72, 2169-2197

Poster

## The mineralogy, geochemistry and PGE variations in LG and MG chromitites of the northwestern Bushveld Complex, South Africa

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The chromitite layers of the Bushveld Complex, South Africa are known to be among the most important reserves of Cr and platinum-group element (PGE). Here we report detailed information on small-scale, vertical variations in mineral chemistry, textures and especially PGE mineralization in the Lower and Middle Group chromitites of the Bushveld Complex. Profiles from one drill core covering 5 complete chromitite layers (LG6-MG2) including adjacent pyroxenitic host rocks were analyzed by electron microprobe, LA-ICP-MS and whole-rock analysis of the platinum-group element (PGE) concentrations. In addition the platinum-group and base metal sulfide assemblages were studied by mineral liberation analysis.

Detailed whole-rock analyses of PGE concentrations along vertical profiles reveal elevated PGE concentrations for all layers compared to the pyroxenite host rocks. Significant internal variations occur throughout all profiles with enrichments at hanging and/or footwalls. The enriched nature of chromitites in PGE compared to background concentrations of the host pyroxenite is a general feature, independent of the layer thickness. Quantification of the PGE phase assemblage depicts two principal groups: the LG6, LG6 and MG1 are dominated by the malanite series, laurite and PGE sulfarsenides, while the MG2 and MG2 II layers are characterized by laurite, PGE sulfides and Pt-Fe-Sn and PGE-Sb-Bi-Pb alloys. PGE-tellurides and bismuthotellurides are largely absent.

The reason for these variations might be the post-cumulus redistribution of PGE in the chromitite crystal mush, which is strongly indicated by textural and chemical variations along all investigated chromitites. Textural analyses suggest that the primary chromite texture were coarsened by a combination of adcumulus growth and textural equilibration, while compaction of the crystal mush played only a minor role. The mineral composition was also modified by post-cumulus processes, however, contrary to previous studies, we attribute these changes to influxes from outside the layers in an open system, instead of chemical equilibration in a closed system. Thus, the investigation and evaluation of post-cumulus changes in the chromitites of the Bushveld Complex might be also of economic importance, as these changes could provide valuable information on possible PGE redistribution.

Talk

## An unusual Fluorbritholite-(Ce)-rich REE deposit in a fenite body of Devonian granites, Central Argentina.

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The middle Devonian Las Chacras-Potrerillos batholith, San Luis province, Central Argentina, is composed of A-type monzonite and granite suites. The REE deposit "Rodeo de Los Molles" is situated in a fenitized zone in a biotite-monzogranite at the northern margin of the batholith. The fenitization is accompanied by the transformation of monzogranite to alkali-feldspar (±quartz) syenite compositions. REE-rich mineral assemblages occur as isolated patches as well as in vein structures consisting of intergrown britholite group minerals (BGM) with REE carbonates, fluorapatite, allanite, fluorite, titanite, hydrothermal zircon, albite and quartz. The patchy REE mineralizations are located in small syenite bodies enclosed in areas with stronger fenitization. Small and large-scale vein structures are up to 1m thick and cut the fenitization zone. Britholite group minerals are found in unusual high amounts at Rodeo de Los Molles, reaching 80 Vol% within vein structures, whereas in isolated patches britholite is mostly altered to bastnaesite, reaching only 10 Vol%. The later suggests the presence of fluids rich in $CO_2$, leading to the dissolution of britholite and its replacement by REE carbonates. Britholite minerals typically occur as both irregular masses as well as discrete crystals with a strong zonation. Exsolution textures of fluorbritholite-(Ce) within fluorapatite suggest an initial formation at higher temperature with exsolution upon cooling. In contrast to comparable britholite studies (e.g. Macdonald et al., 2013; Uher et al., 2015), the LREE contents of the BGMs at Rodeo de los Molles are among the highest reported so far, reaching a chondrite normalized concentration of nearly 500 000. A detailed electron-microprobe study also revealed a major composition gap between apatite and britholite group minerals, ranging from about 8% to 55% of the britholite component. The dominant substitution mechanism is $REE^{3+} + Si^{4+} = Ca^{2+} + P^{5+}$. This suggests a miscibility gap between the apatite-supergroup members.

Macdonald, R, Baginski, B., Dzierzanowski, P., Jokubauskas, P. (2013): Apatite-supergroup minerals in UK Paleogene granites: composition and relationship to host-rock composition, Eur. J. Mineral., 25: 461-671.

Uher, P., Ondrejka, M., Bacik, P., Broska, I., Konecny, P. (2015): Britholite, monazite, REE carbonates and calcite: products of hydrothermal alteration of allanite and apatite in A-type granite from Stupné, western Carpathians, Slovakia. Lithos 236-237: 212-225.

Poster

## Properties, Processes and Products of Evolving Hydrothermal Fluids at the Los Bronces Porphyry Cu(-Mo) deposit, Central Chile

**Gerrit Müller**[1], **Katja Deckart**[2,3], **Daniel Moncada**[2], **Thorsten Geisler**[1], **Mauricio Carranza**[4], **Pablo Cabello**[4]

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The Mio-Pliocene Río Blanco-Los Bronces Porphyry Cu(-Mo) mineralisation represents one of the largest known mineral deposits in Central Chile and is located in the higher Andes mountain range, about 65 km northeast from the Chilean capital Santiago. Hydrothermal fluids, which exsolved from unexposed composite plutons, interacted between 8.4 and 4.5 Ma with middle to upper Miocene quartz monzodioritic intrusions (San Francisco Batholith) and the Farellones Andesite host rock. Fluid-related processes have led to subsequent stages of alteration, brecciation, and resealing of these host rocks, as well as to economically important deposition of base-metal sulphides. This study intended to reconstruct the evolving PTVX conditions of the system during fluid interaction. Therefore, we studied in detail the altered and mineralised assemblages. Furthermore, we coupled microthermometric and Raman spectroscopic analyses of petrographically well examined Fluid Inclusion Assemblages (FIA), enabling the direct measurement of original fluid properties of several FIA. The combination of microthermometry and Raman spectroscopy allowed a quantitative estimate on entrapment density, pressure, and depth, using $CO_2$-properties. The latter was detected at Los Bronces for the first time. In other FIA, spectroscopically determined carbonate equilibria were used as pH-proxy. Early potassic vein- and alteration assemblages (Bt-Kfs-Qtz-Ccp-Bn-Py) apparently correlate with non-boiling, aqueous-carbonic, highly saline (5.7 - 7.26 mol/L $NaCl_{eq.}$), high-temperature (> 400°C), alkaline FIA with base-metal oxides and salt crystals. In most samples, these are superimposed by transitional chloritic (Chl-Ser-Qtz-Py-Bn(-Ccp)) and late-stage sericitic (Ser-Qtz-Py-Bn(-Ccp)) alteration-mineralisation assemblages and by less saline (5.4 - 6.1 mol/L $NaCl_{eq.}$), low-temperature (~290°C), acidic FIA with only small amounts of sulphide daughter minerals. This change of the fluid properties and products is interpreted as a result of metasomatic exchange, cooling, depletion, and/or mixing of different magmatic fluid sources possibly with meteoric waters during late stages and contributions of condensed vapor. The coexistence of secondary liquid- and vapor-rich, $CO_2$-bearing FIA in quartz from younger veins (transitional to late-stage) indicate that phase separation becomes an important precipitation mechanism during late stages under hydrostatic pressure at a depth of 1500 to 2400 m below the uplifted and eroded (≤ 800 m) paleo-surface. Geochemical trends, such as (i) a decreasing temperature and pH, (ii) a depletion in salt- and metal-content, and (iii) superimposition-relationships, suggest a fluid chronology. Although no significant supergene enrichment altered the system, repeated hydrothermal pulses and brecciation-sealing-rebrecciation cycles, superimposing each other complicate this interpretation. More data from different alteration zones is needed to further verify or discard the model.

Talk

## Au-rich VMS mineralisation at ODP Hole 786B: evidence for magmatic input in the hydrothermal system

**Clifford Patten**[1], **Iain Pitcairn**[2]

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The metals enriched in volcanogenic massive sulphide (VMS) deposits, hydrothermal ore deposits forming in extensional tectonic settings on the seafloor, are commonly considered to come from two main sources: hydrothermal alteration zones in the lower oceanic crust and exsolving magmatic volatiles. The metal budget of VMS deposits is extensive with many precious metals (Au, Ag) and semi-metals (As, Sb, Te, Se, Bi, Tl, Cd) being enriched alongside base metals. It has been suggested that enrichments of the precious and semi-metals such as Au, Se, Mo, Ag, Te, and Bi in Au-rich VMS deposits can indicate significant input of magmatic volatiles into the hydrothermal system (e.g. Yang and Scott 2002). This suite of metals, however, is also partly mobilised by hydrothermal alteration reactions in the lower sheeted dyke section of the oceanic crust (e.g. Patten et al. 2016). Constraints of the trace element signature of magmatic volatile input in hydrothermal systems would aid understanding of the causes for the variable metal budgets in Au-VMS deposits and the role of magmatic processes on VMS deposit formation.

Oceanic drilling program (ODP) Hole 786B in the Izu-Bonin forearc is one of the only deep drill holes into supra-subduction oceanic crust recovering over 700 m of basement rocks from the volcanic section to the upper sheeted dyke complex, including a conspicuous 30 m thick transitional zone in the lowermost section of the core. This mineralised zone is characterised by pyrite with minor chalcopyrite, marcasite, sphalerite, galena, bornite and covellite variably distributed within the mineralisation. Negative in-situ $\delta^{34}S$ pyrite analyses and acidic mineral alteration assemblage indicate a strong magmatic input in the hydrothermal system. Whole rock chemistry and magmatic modelling of the overlying volcanic section also suggests magmatic degassing during late magmatic differentiation with significant metal mobilisation. Enrichment in Au, Se, Se, Mo; Te and Bi in the mineralised zone is interpreted as being sourced by the magmatic fluids whereas the As and Sb could have been leached by hydrothermal fluids.

References:

Patten CGC, Pitcairn IK, Teagle DAH, Harris M (2016) Mobility of Au and related elements during the hydrothermal alteration of the oceanic crust: implications for the sources of metals in VMS deposits. Miner Depos 51:179-200

Yang K, Scott SD (2002) Magmatic degassing of volatiles and ore metals into a hydrothermal system on the modern sea floor of the eastern Manus back-arc basin, western Pacific. Econ Geol 97:1079–1100

Poster

## Characterization of Native Silver and Associated Minerals in the Vinoren Area, Kongsberg Silver District

**Enrico Ribacki**[1], **Uwe Altenberger**[1], **Kåre Kullerud**[2], **Christina Günter**[1]

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Spectacular pieces of native silver from the Kongsberg Mining District in southern Norway are well known all over the world. The hydrothermal epigenetic silver deposits are located 80 km west of Oslo in the Sveconorwegian orogenic belt.

The mines are situated along north-south trending Fahlband zones. These strongly deformed sulfide impregnated features of hydrothermal origin appear independently from the surrounding host rock and are related to shear zones. The Kongsberg lithotectonic unit is mainly characterized by Proterozoic metamorphic rocks. Magmatism and extensional stretching of the Permian Oslo Rift shaped this area and led to a wide spreading hydrothermal activity (Kotková et al., 2017). The Sveconorwegian basement and the Fahlbands are cross-cut by east-west running quartz and calcite veins which were formed along tension fissures caused by normal faulting. These veins represent various generations of fluid transport and carry sulfides of base and noble metals.

The crystallization of native silver exclusively occurs were silver bearing calcite veins intersect the sulfide enriched Fahlband structures.

The studied Ringnesgangen Silver Mine branches off from the main shaft of the Norske Løve Mine which is located in the northern part of the Kongsberg area, the southern Vinoren. The present work reveals new information of the native silver origin as well as the paragenetic silver ores and the associated minerals in the Kongsberg Mining District.

The first results of the investigation on silver-bearing samples show solid solutions in the Ag-Hg-Sb ternary system. Additionally, silver minerals like antimonial silver, tetrahedrite/freibergite, and polybasite are often surrounded by a rim of various Ni-Co-Fe-Sulfarsenides. Associated ore minerals like pyrrhotite, arsenopyrite, pyrite, sphalerite with chalcopyrite exsolutions, and galena occur in direct contact to the silver minerals. In fact, the regional variations in the Ag-Hg-Sb concentrations and the presence of Ni-Co-Fe-Sulfarsenides show several stages of silver mineralization and the interaction of early phases with Ag-bearing fluids through remobilization (Kotková et al., 2017).

The studied samples of the Ringnesgangen Silver Mine show no detectable bismuth although due to the mineral paragenesis, the deposits in the Kongsberg area can be classified as Five-Element (Ag-Ni-Co-As-Bi) ore deposits (Kissin & Mango, 2014).

Kissin, S. A., and H. Mango. “Silver Vein Deposits.” Treatise on Geochemistry 2nd Edition, Vol. 13 (2014): 425-432.

Kotková, J., K. Kullerud, V. Šrein, M. Drábek, and R. Škoda. “The Kongsberg silver deposits, Norway: Ag-Hg-Sb mineralization and constraints for the formation of the deposits.” *Mineralium Deposita* 53, no. 4 (2018): 531-545.

Talk

## Metal-bearing brines in tonalites in the Oman ophiolite and their relation to VMS deposits

**Lisa Richter, Larryn Diamond**

*University of Bern, Switzerland*

The Oman ophiolite consists of a complete section of oceanic lithosphere, including High-level intrusives, a sheeted dike complex, Late intrusives and basaltic extrusive sequences (axial Geotimes and off-axis Lasail, followed by arc-like Alley and Boninitic Alley). Volcanogenic massive sulfide (VMS) deposits are present at Geotimes/Lasail contacts, as well as deep within all four volcanic sequences (Gilgen et al., 2014). Although all the volcanic rocks have been pervasively altered to minerals characteristic of seawater infiltration, the source of metals in the hydrothermal fluids that fed these deposits is still under debate. Previous studies on VMS systems suggest that, besides seawater with slightly increased salinity (Nehlig et al., 1994), magmatic fluid exsolved from intrusives may also be involved (e.g. Galley et al., 2003; Sillitoe et al. 1996).

Two phases of intrusions are recognized in the Oman crust, each comprising gabbros and tonalites (Haase et al., 2016 and references therein): (i) early MORB-like High-level/P1 intrusives of Geotimes age sitting at the base of the sheeted dike complex and (ii) later tholeiitic to boninitic Late intrusives/P2 formed during Lasail and Alley volcanism, the latter indicating a subduction signature. These Late intrusives occur within the volcanic sequences and are contemporaneous with VMS deposits hosted by Lasail and Alley lavas (Gilgen et al., 2014).

In order to test a possible contribution of magmatic fluid to the VMS systems in the Oman ophiolite we characterized the salinities, chemical compositions and especially the metal contents of fluid inclusions in the quartz-rich, water-saturated parts of Late tonalites. These pseudosecondary inclusion assemblages within magmatic quartz consist of heterogeneously trapped mixtures of liquid-rich liquid+vapor+halite inclusions and coexisting vapor-rich liquid+vapor inclusions. The liquid-rich endmembers are highly saline, with around 50 wt.% NaCl eq and elevated contents of Cu, Zn, Mn, Fe, Pb and Ag, as detected by Laser-ICP-MS.

Our on-going research will use mass-balance arguments to assess the contribution of these metal-bearing brines to the VMS systems, as well comparative studies of fluid inclusions in stockwork zones directly underlying VMS deposits.

References:

Galley et al. (2007): GAC, Spec Pub 5: 141–162

Gilgen et al. (2014): Econ Geol 109: 1585–1610

Nehlig et al. (1994): J Geophys Res 99: 4703–4713

Haase et al. (2016): Contrib Mineral Petrol 171: 46

Sillitoe et al. (1996): Econ Geol 91: 204–212

# Topic 10: Fossil ecosystems

## 10a) The early `Explosion of Life´ – from the Cambrian innovations to the great Ordovician radiations

Talk

### The Early Palaeozoic marine diversifications: some causes and consequences

**David Harper**

*Palaeoecosystems Group, Department of Earth Sciences, Durham University, United Kingdom*

Early Palaeozoic marine life, its diversity and evolution, was first driven by an extended Cambrian Explosion, a phase of metazoan body building and radiation of higher taxa, which was apparently obstructed by major oceanic changes including periodic and widespread anoxia during the late Cambrian. The Great Ordovician Biodiversification Event was similarly protracted, but with a clear trajectory, stimulated by a plankton radiation rooted in the late Cambrian that segued into the diachronous diversifications of benthic and nektonic groups in terms of both individual clades and provinces through the Ordovician, and eventually the construction of metazoan-dominated reef ecosystems. There are clear patterns and trends within phyla too; for example, the Brachiopoda apparently peaked three times: the first in the Tremadocian and Floian when holdovers from the Cambrian evolutionary fauna climaxed and alpha diversity increased; the Darriwilian peak is particularly apparent in Baltoscandian where the orthides and strophomenides dominated, associated with increased gamma diversity, and finally in the Katian when the widespread development of carbonates, buildups and reefs, provided new niches for beta diversifications. Global cooling, higher oxygen levels, increased nutrient flux in the oceans, and biotic interactions have been invoked as key drivers. Against this background of increasing numbers of species, genera and families the ecosystem was tested by a series of increasingly intense ice-house intervals culiminating in the short, sharp end Ordovician glacigene episode. The associated first and second strikes of the end Ordovician extinction were not clade specific but affected a range of environments from the deep sea to the tropical shelves. The extinction was a marked taxonomic event but did little to alter the structure of the Early Palaeozoic ecosystem which would essentially survive intact until the end Permian extinction.

Talk

### Global scale diversity of phytoplankton in the Early Palaeozoic and its palaeoecological significance

**David Kroeck[1], Claude Monnet[1], Gary Mullins[2], Axelle Zacaï[1], Thomas Servais[1]**

*[1]Université de Lille, France; [2]Robertson, a CGG Company, Llandudno, UK*

Phytoplanktic organisms play an important role in Earth's ecosystems. They constitute a major part of the base of marine food chains and represent the starting point for nearly all biological activity in the modern marine realm. Furthermore, phytoplankton is the biggest producer of oxygen and responsible for most of the carbon dioxide transfer from the atmosphere to the oceans. Therefore, it can be inferred that changes in ancient phytoplankton populations in the Early Palaeozoic had considerable effects on palaeoecosystems. Hence, the study of ancient phytoplankton diversity on a regional and global scale is of great interest because it can provide valuable insights into the evolution of marine ecosystems, including during the Great Ordovician Biodiversification Event (GOBE).

Using a database built from all published literature, including taxonomic, geographic and stratigraphic information, with more than 6,000 species, a comprehensive investigation of the diversity of Palaeozoic phytoplankton is conducted. By highlighting the evolutionary consequences of diversification and extinction events the results allow not only to assess the phytoplankton evolutionary dynamics, but also, on a larger scale, its influence on the marine ecosystems.

The diversity curves show clear trends with several diversification and extinction events. The Early Palaeozoic is generally characterized by high diversity values, punctuated by small extinction. A protracted trend of increasing diversity begins in late Cambrian times and contiues into the Ordovician with a peak in the Darriwillian. A distinct diversity decline occurs in the Late Ordovician. The diversity curve roughly parallels sea-level changes. A long-term sea level rise from the earliest Cambrian to the Late Ordovician, resulting in the expansion of shelf regions and therefore available ecospace, is probably an important factor in the observed general increase in phytoplankton diversity during this interval.

During the late Cambrian and Ordovician major changes in the marine trophic web took place, such as the radiation of zooplanktonic organisms, a major diversification of suspension feeders, and the development of planktotrophy in invertebrate larvae. Our study also aims to examine to what extent this modification of the marine trophic structures, and moreover the diversification of the major Ordovician fossil groups, is related to phytoplankton evolution. It is possible that the availability of increased quantities of phytoplankton in the late Cambrian and Lower Ordovician permitted the synchronous radiation of zooplanktic and nektic groups, as well as benthic suspension feeders.

Talk

## Major diversification pulses during the GOBE linked to the Ordovician climate record

**Oliver Lehnert[1,2,3], Peep Männik[4], John E. Repetski[5], Rongchang Wu[2], Michael M. Joachimski[1], Mikael Calner[6], Björn Kröger[7], Jaak Nõlvak[4], Thomas Servais[8], David A. T. Harper[9], Renbin Zhan[2]**

*[1]GeoZentrum Nordbayern, University of Erlangen-Nürnberg, Germany; [2]Key Laboratory of Economic Stratigraphy and Palaeogeography (NIGP, CAS), Nanjing, China; [3]Faculty of Environmental Sciences, Department of Environmental Geosciences, Czech University of Life Sciences Prague, Czech Republic; [4]Institute of Geology at Tallinn University of Technology, Estonia; [5]U.S. Geological Survey-Emeritus. Reston, USA; [6]Department of Geology, Lund University, Sweden; [7]Finnish Museum of Natural History, PO Box 44, Fi-00014 University of Helsinki, Finland; [8]University of Lille Lille, France; [9]Palaeoecosystems Group, Department of Earth Sciences, Durham University, UK*

Biological radiation patterns during the Great Ordovician Biodiversification Event (GOBE) and their triggers have been widely discussed. The GOBE was manifested by multiple evolutionary pulses and major ecosystem changes after the introduction of innovative body plans during the Cambrian. Marine faunal groups diversified at different stratigraphic levels and at different times on different palaeoplates depending on available ecospace, climatic conditions, and ocean currents. Besides long-term plate tectonic processes, global climatic changes had major influences on diversity trends.

We elucidate the changes in climate prior to the culmination of the Early Palaeozoic Icehouse. The Ordovician $\delta^{18}O$ trend (conodont apatite) presented by Trotter et al. (2008) indicated an overall climate cooling. Investigations at different time slices suggests that the various glacial and interglacial intervals started during the Middle Ordovician. Our sparse $\delta^{18}O$ data from Laurentia imply a colder interval at the Cambrian/Ordovician transition presumably boosting the plankton revolution. It is followed by a temperature increase and warm climatic conditions during the mid-Tremadocian with a shift to colder climates in the latest Tremadocian and Floian.

Climate fluctuations are recorded in the Floian and Dapingian of Baltoscandia but a prominent shift to colder conditions is observed in the Darriwilian *Y. crassus* conodont zone (within an overall cooling across the Mid-Darriwilian Isotopic Carbon Excursion, MDICE). One succession (Tingskullen core, Öland, Sweden) has the most complete MDICE record in the world and its $\delta^{18}O$ record indicates a dramatic cooling in this interval indicating the contemporaneous build-up of a larger ice cap in the polar regions of Gondwana. Increased nutrient availability is probably corresponding to the rising limb of the MDICE. It may have triggered the major diversification in brachiopods at the family level and in cephalopods, the main predators in the Ordovician food web showing an initial diversity peak during this interval.

After shifting into icehouse conditions in the Middle Ordovician, the build-up of extensive ice-caps on south-polar Gondwana led to major regressions, subaerially exposing vast areas of palaeocontinents previously covered by epicontinental seas. The rise and demise of complex ecosystems and their distribution, pulses in reef evolution, as well as many bioevents, were presumably linked to associated glacially-driven, major eustatic sea-level changes. Moreover the exposure of continental areas from tropics to high latitudes during the major glaciations probably enabled the terrestrialisation of land plants on different palaeoplates.

Talk

## Eye Diversification in the Ordovician

**Brigitte Schoenemann[1], Euan N.K. Clarkson[2]**

*[1]University of Cologne, Germany; [2]University of Edinburgh, UK*

The eyes of trilobites have lenses of calcite, set in an organic base. They are not often preserved in Cambrian trilobites, usually because the visual surface is encircled by a continuous circum-ocular suture, formed from the palpebral suture above and the ocular suture, which runs along the lower edge of the visual surface. In such instances, the visual rsurface, with all its lenses, dehisced as a unit when moulting, rather than remaining attached to the librigena. Ordovician trilobites, however, generally retained the visual surface with the librigena, except in one group (the calymenids0, so the record is much more complete

Most of the eyes known in Cambrian trilobites are holochroal; they have many small, contiguous lenses with a common corneal sheet of thin calcite covering them. The majority have the basic, standard design, being reniform, with a relatively narrow, laterally directed visual field. It is only in some representatives of the late Cambrian (Furongian) Olenidae that the eyes became more spherical, thus encompassing a broader visual field; they are the on ly trilobites that broke away from the standard reniform design. *Ctenopyge, Sphaerophthalmus* and *Jujuyaspis* are typical examples. This was evidently an adaptation to habitat.

From the early Ordovician onwards, however, there was dramatic 'explosion' of holochroal eye types, related to colonisation of new habitats and different modes of life. In some asaphids, and rarely in encrinurids for example, the eyes may become set on rigid stalks, and below the visual surface sensory pits may be present, somehow related to the visual input. The pelagic cyclopygids, which may have swum upside down, and some other genera have enormous hypertrophied eyes as in the living amphipod *Cystisoma.* Lenses range from being very thin (olenids) lenses forming elongated prisms in the thick shelled asaphids. Eye-reduction and loss for trilobites living in darkness is well documented.

The most dramatic modification however, concerns the origin of the schizochroal eye in the early Ordovician, confined to the phacopid trilobites (L. Ord- L. Dev). Here the lenses are likewise calcitic and internally differentiated; they are much larger, isolated from each other, each with a separate cornea. The lenses are very thick and internally diffentiated. They were probably derived by paedomorphosis from a holochroal precursor. They are unique in the animal kingdom and as with all trilobite eyes, their structure and optics remain the subject of intensive research.

Talk

## Different species or just ecophenotypes? Population analyses of the early Palaeozoic acritarch genus Liliosphaeridium from the Ordovician of Öland, Sweden

**Thomas Servais[1], David M. Kröck[1], Mats E. Eriksson[2], Anders Lindskog[2], Claude Monnet[1], Axel Munnecke[3]**

*[1]Evo-Eco-Paléo, UMR 8198 CNRS, Université de Lille, Avenue Paul Langevin, Bâtiment SN5, Cité Scientifique, 59655 Villeneuve-d'Ascq, France.; [2]Lithosphere and Biosphere Science, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden; [3]Geozentrum Nordbayern, Paläobiologie, Friedrich-Alexander Universität Erlangen-Nürnberg, Löwenichstrasse 28, 91054 Erlangen, Germany;* thomas.servais@univ-lille.fr

The classification of acritarchs remains a major problem concerning the study of this group, which is considered as representing a major part of the organic-walled phytoplankton of the Palaeozoic. It can be assumed that a large part of the taxa described in literature are not real biological entities but rather represent different (eco-) phenotypes. Morphological changes had been interpreted mostly as a result of chronological evolution, whereas in many cases it can be assumed that they reflect changing environmental conditions.

Previous investigations (e.g. Servais et al. 2004) show that a large intraspecific morphological variety can indeed be observed within most 'galeate' acritarchs. Many of the described taxa represent only individual morphotypes in a wider, unimodal and continuous range of morphologies, and therefore cannot be considered as distinct species, or even genera.

Here we present new studies from different sections of the Middle Ordovician of Öland, Sweden. A variation, that could be considered as ecophenotypical, is observed in different morphotypes of the 'peteinoid' acritarch genus *Liliosphaeridium*, with a transition from *L. hypertrophicum* to *L. intermedium* and *L. kaljoi*, and another morphological variation from *L. pocillum* to *L. brevicalix* and *L. tintinnabulum*.

Although the biological affinity of acritarchs remains enigmatic, for the greater part of the group a relationship to dinoflagellates is assumed. Some studies on dinoflagellate cysts, including both investigations on subrecent material and culture experiments on living dinoflagellates (e.g. Kokinos & Anderson 1995; Ellegaard 2000; Mertens et al. 2009), show that the highly variable cyst morphology is dependent on environmental factors, such as temperature and salinity.

Considering that many acritarchs, such as *Liliosphaeridium*, possibly represent resting cysts of dinoflagellate-like organisms, it is reasonable to suppose that in the Middle Ordovician of Öland the different morphologies also represent a reaction to changing environmental conditions.

Ellegaard, M. 2000. Variations in dinoflagellate cyst morphology under conditions of changing salinity during the last 2000 years in the Limfjord, Denmark. *Review of Palaeobotany and Palynology*, **109**, 65-81.

Kokinos, J. P. & Anderson, D., M. 1995. Morphological development of resting cysts in cultures of the marine dinoflagellate *Lingulodinium polyedrum* (= *L. machaerophorum*). *Palynology*, **19**, 143-166.

Mertens, K.N. et al. 2009. Process length variation in cysts of a dinoflagellate, *Lingulodinium machaerophorum*, in surface sediments: Investigating its potential as salinity proxy. *Marine Micropalaeontology*, **70**, 54-69.

Servais, T. et al. 2004. Population dynamics of galeate acritarchs at the Cambrian-Ordovician transition in the Algerian Sahara. *Palaeontology*, **47** (2), 395-414.**vid Harper**

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Talk

## Global scale diversity of phytoplankton in the Early Palaeozoic and its palaeoecological significance

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Talk

## Major diversification pulses during the GOBE linked to the Ordovician climate record

**Oliver Lehnert**[1,2,3], **Peep Männik**[4], **John E. Repetski**[5], **Rongchang Wu**[2], **Michael M. Joachimski**[1], **Mikael Calner**[6], **Björn Kröger**[7], **Jaak Nõlvak**[4], **Thomas Servais**[8], **David A. T. Harper**[9], **Renbin Zhan**[2]

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Talk

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**Thomas Servais**[1], **David M. Kröck**[1], **Mats E. Eriksson**[2], **Anders Lindskog**[2], **Claude Monnet**[1], **Axel Munnecke**[3]

*[1]Evo-Eco-Paléo, UMR 8198 CNRS, Université de Lille, Villeneuve-d'Ascq, France.; [2]Lithosphere and Biosphere Science, Department of Geology, Lund University, Lund, Sweden; [3]Geozentrum Nordbayern, Paläobiologie, Friedrich-Alexander Universität Erlangen-Nürnberg, Erlangen, Germany*

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Talk

## The Early Palaeozoic marine diversifications: some causes and consequences

**David Harper**

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Early Palaeozoic marine life, its diversity and evolution, was first driven by an extended Cambrian Explosion, a phase of metazoan body building and radiation of higher taxa, which was apparently obstructed by major oceanic changes including periodic and widespread anoxia during the late Cambrian. The Great Ordovician Biodiversification Event was similarly protracted, but with a clear trajectory, stimulated by a plankton radiation rooted in the late Cambrian that segued into the diachronous diversifications of benthic and nektonic groups in terms of both individual clades and provinces through the Ordovician, and eventually the construction of metazoan-dominated reef ecosystems. There are clear patterns and trends within phyla too; for example, the Brachiopoda apparently peaked three times: the first in the Tremadocian and Floian when holdovers from the Cambrian evolutionary fauna climaxed and alpha diversity increased; the Darriwilian peak is particularly apparent in Baltoscandian where the orthides and strophomenides dominated, associated with increased gamma diversity, and finally in the Katian when the widespread development of carbonates, buildups and reefs, provided new niches for beta diversifications. Global cooling, higher oxygen levels, increased nutrient flux in the oceans, and biotic interactions have been invoked as key drivers. Against this background of increasing numbers of species, genera and families the ecosystem was tested by a series of increasingly intense ice-house intervals culiminating in the short, sharp end Ordovician glacigene episode. The associated first and second strikes of the end Ordovician extinction were not clade specific but affected a range of environments from the deep sea to the tropical shelves. The extinction was a marked taxonomic event but did little to alter the structure of the Early Palaeozoic ecosystem which would essentially survive intact until the end Permian extinction.

Talk

## Global scale diversity of phytoplankton in the Early Palaeozoic and its palaeoecological significance

**David Kroeck[1], Claude Monnet[1], Gary Mullins[2], Axelle Zacaï[1], Thomas Servais[1]**

*[1]Université de Lille, France; [2]Robertson, a CGG Company, Llandudno, UK*

Phytoplanktic organisms play an important role in Earth's ecosystems. They constitute a major part of the base of marine food chains and represent the starting point for nearly all biological activity in the modern marine realm. Furthermore, phytoplankton is the biggest producer of oxygen and responsible for most of the carbon dioxide transfer from the atmosphere to the oceans. Therefore, it can be inferred that changes in ancient phytoplankton populations in the Early Palaeozoic had considerable effects on palaeoecosystems. Hence, the study of ancient phytoplankton diversity on a regional and global scale is of great interest because it can provide valuable insights into the evolution of marine ecosystems, including during the Great Ordovician Biodiversification Event (GOBE).

Using a database built from all published literature, including taxonomic, geographic and stratigraphic information, with more than 6,000 species, a comprehensive investigation of the diversity of Palaeozoic phytoplankton is conducted. By highlighting the evolutionary consequences of diversification and extinction events the results allow not only to assess the phytoplankton evolutionary dynamics, but also, on a larger scale, its influence on the marine ecosystems.

The diversity curves show clear trends with several diversification and extinction events. The Early Palaeozoic is generally characterized by high diversity values, punctuated by small extinction. A protracted trend of increasing diversity begins in late Cambrian times and contiues into the Ordovician with a peak in the Darriwillian. A distinct diversity decline occurs in the Late Ordovician. The diversity curve roughly parallels sea-level changes. A long-term sea level rise from the earliest Cambrian to the Late Ordovician, resulting in the expansion of shelf regions and therefore available ecospace, is probably an important factor in the observed general increase in phytoplankton diversity during this interval.

During the late Cambrian and Ordovician major changes in the marine trophic web took place, such as the radiation of zooplanktonic organisms, a major diversification of suspension feeders, and the development of planktotrophy in invertebrate larvae. Our study also aims to examine to what extent this modification of the marine trophic structures, and moreover the diversification of the major Ordovician fossil groups, is related to phytoplankton evolution. It is possible that the availability of increased quantities of phytoplankton in the late Cambrian and Lower Ordovician permitted the synchronous radiation of zooplanktic and nektic groups, as well as benthic suspension feeders.

Talk

## Major diversification pulses during the GOBE linked to the Ordovician climate record

**Oliver Lehnert[1,2,3], Peep Männik[4], John E. Repetski[5], Rongchang Wu[2], Michael M. Joachimski[1], Mikael Calner[6], Björn Kröger[7], Jaak Nõlvak[4], Thomas Servais[8], David A. T. Harper[9], Renbin Zhan[2]**

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Biological radiation patterns during the Great Ordovician Biodiversification Event (GOBE) and their triggers have been widely discussed. The GOBE was manifested by multiple evolutionary pulses and major ecosystem changes after the introduction of innovative body plans during the Cambrian. Marine faunal groups diversified at different stratigraphic levels and at different times on different palaeoplates depending on available ecospace, climatic conditions, and ocean currents. Besides long-term plate tectonic processes, global climatic changes had major influences on diversity trends.

We elucidate the changes in climate prior to the culmination of the Early Palaezoic Icehouse. The Ordovician $\delta^{18}O$ trend (conodont apatite) presented by Trotter et al. (2008) indicated an overall climate cooling. Investigations at different time slices suggests that the various glacial and interglacial intervals started during the Middle Ordovician. Our sparse $\delta^{18}O$ data from Laurentia imply a colder interval at the Cambrian/Ordovician transition presumably boosting the plankton revolution. It is followed by a temperature increase and warm climatic conditions during the mid-Tremadocian with a shift to colder climates in the latest Tremadocian and Floian.

Climate fluctuations are recorded in the Floian and Dapingian of Baltoscandia but a prominent shift to colder conditions is observed in the Darriwilian *Y. crassus* conodont zone (within an overall cooling across the Mid-Darriwilian Isotopic Carbon Excursion, MDICE). One succession (Tingskullen core, Öland, Sweden) has the most complete MDICE record in the world and its $\delta^{18}O$ record indicates a dramatic cooling in this interval indicating the contemporaneous build-up of a larger ice cap in the polar regions of Gondwana. Increased nutrient availability is probably corresponding to the rising limb of the MDICE. It may have triggered the major diversification in brachiopods at the family level and in cephalopods, the main predators in the Ordovician food web showing an initial diversity peak during this interval.

After shifting into icehouse conditions in the Middle Ordovician, the build-up of extensive ice-caps on south-polar Gondwana led to major regressions, subaerially exposing vast areas of palaeocontinents previously covered by epicontinental seas. The rise and demise of complex ecosystems and their distribution, pulses in reef evolution, as well as many bioevents, were presumably linked to associated glacially-driven, major eustatic sea-level changes. Moreover the exposure of continental areas from tropics to high latitudes during the major glaciations probably enabled the terrestrialisation of land plants on different palaeoplates.

Talk

## Eye Diversification in the Ordovician

**Brigitte Schoenemann[1], Euan N.K. Clarkson[2]**

*[1]University of Cologne, Germany; [2]University of Edinburgh, UK*

The eyes of trilobites have lenses of calcite, set in an organic base. They are not often preserved in Cambrian trilobites, usually because the visual surface is encircled by a continuous circum-ocular suture, formed from the palpebral suture above and the ocular suture, which runs along the lower edge of the visual surface. In such instances, the visual rsurface, with all its lenses, dehisced as a unit when moulting, rather than remaining attached to the librigena. Ordovician trilobites, however, generally retained the visual surface with the librigena, except in one group (the calymenids0, so the record is much more complete

Most of the eyes known in Cambrian trilobites are holochroal; they have many small, contiguous lenses with a common corneal sheet of thin calcite covering them. The majority have the basic, standard design, being reniform, with a relatively narrow, laterally directed visual field. It is only in some representatives of the late Cambrian (Furongian) Olenidae that the eyes became more spherical, thus encompassing a broader visual field; they are the on ly trilobites that broke away from the standard reniform design. *Ctenopyge, Sphaerophthalmus* and *Jujuyaspis* are typical examples. This was evidently an adaptation to habitat.

From the early Ordovician onwards, however, there was dramatic ‘explosion’ of holochroal eye types, related to colonisation of new habitats and different modes of life. In some asaphids, and rarely in encrinurids for example, the eyes may become set on rigid stalks, and below the visual surface sensory pits may be present, somehow related to the visual input. The pelagic cyclopygids, which may have swum upside down, and some other genera have enormous hypertrophied eyes as in the living amphipod *Cystisoma.* Lenses range from being very thin (olenids) lenses forming elongated prisms in the thick shelled asaphids. Eye-reduction and loss for trilobites living in darkness is well documented.

The most dramatic modification however, concerns the origin of the schizochroal eye in the early Ordovician, confined to the phacopid trilobites (L. Ord- L. Dev). Here the lenses are likewise calcitic and internally differentiated; they are much larger, isolated from each other, each with a separate cornea. The lenses are very thick and internally diffentiated. They were probably derived by paedomorphosis from a holochroal precursor. They are unique in the animal kingdom and as with all trilobite eyes, their structure and optics remain the subject of intensive research.

Talk

## Different species or just ecophenotypes? Population analyses of the early Palaeozoic acritarch genus Liliosphaeridium from the Ordovician of Öland, Sweden

**Thomas Servais[1], David M. Kröck[1], Mats E. Eriksson[2], Anders Lindskog[2], Claude Monnet[1], Axel Munnecke[3]**

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The classification of acritarchs remains a major problem concerning the study of this group, which is considered as representing a major part of the organic-walled phytoplankton of the Palaeozoic. It can be assumed that a large part of the taxa described in literature are not real biological entities but rather represent different (eco-) phenotypes. Morphological changes had been interpreted mostly as a result of chronological evolution, whereas in many cases it can be assumed that they reflect changing environmental conditions.

Previous investigations (e.g. Servais et al. 2004) show that a large intraspecific morphological variety can indeed be observed within most 'galeate' acritarchs. Many of the described taxa represent only individual morphotypes in a wider, unimodal and continuous range of morphologies, and therefore cannot be considered as distinct species, or even genera.

Here we present new studies from different sections of the Middle Ordovician of Öland, Sweden. A variation, that could be considered as ecophenotypical, is observed in different morphotypes of the 'peteinoid' acritarch genus *Liliosphaeridium*, with a transition from *L. hypertrophicum* to *L. intermedium* and *L. kaljoi*, and another morphological variation from *L. pocillum* to *L. brevicalix* and *L. tintinnabulum*.

Although the biological affinity of acritarchs remains enigmatic, for the greater part of the group a relationship to dinoflagellates is assumed. Some studies on dinoflagellate cysts, including both investigations on subrecent material and culture experiments on living dinoflagellates (e.g. Kokinos & Anderson 1995; Ellegaard 2000; Mertens et al. 2009), show that the highly variable cyst morphology is dependent on environmental factors, such as temperature and salinity.

Considering that many acritarchs, such as *Liliosphaeridium*, possibly represent resting cysts of dinoflagellate-like organisms, it is reasonable to suppose that in the Middle Ordovician of Öland the different morphologies also represent a reaction to changing environmental conditions.

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# 10b) Biodiversity dynamics in deep time – signatures of radiation and extinction in the geological record

Talk

## Concepts in palaeontology – how can we categorise animals from the past?

**Joachim Tobias Haug**

*LMU Munich, Germany*

Humans use categorisation as a basic, ubiquitous concept for organising their knowledge of the world. Therefore, it may not be surprising that forming categories is also an everyday part of science. The strategies how such categories are formed and how certain entities are assigned to specific categories are in fact a cruzial part of the scientific method. The quality of the decisions made during this process can heavily influence the outcome and also quality of scientific research. It is therefore absolutely necessary to think and discuss such strategies of categorisation. Palaeontology, as a scientific field in the border area (or limbo?) between the geosciences and biosciences, has its own philosophical framework or epistemological methodology. Yet, also here we base many types of analyses and questions on a priori categorisations. Therefore, I want to discuss cases in which fossils are not easy to categorise. This includes intraspecific as well as interspecific challenges: How can we recognise species as such, let alone other taxonomic units? How can we identify discrete phases or stages in life history? How can we infer ecological guilds of once living organisms? These questions of categorisations are not easy to answer but still heavily influence our interpretation of the biodiversity of the past. Some may argue that due to the uncertainty (or unreliability) of the fossil record it could not be used to answer certain questions. I suggest that this is incorrect. The fossil record provides important clues of the past, yet the statements may be less sharp than one would might want them. However, this also seems to be the case for many biological processes in the modern world. In my view, the major clue is to step back from expecting too sharp conclusions. This view influences how categories in palaeontology can be formed: often there are simply no sharp thresholds separating the one category from the other, but more of a continuum. Trying to break down such a continuum into discrete categories may lead to categories with single entities, which would be practically useless. I advocate a relaxed approach to categorisation in using direct comparison pairs instead of absolute thresholds. This results in less sharp, but in fact more reliable conclusions.

Talk

## Diversity Partitioning in benthic marine ecosystems throughout the Phanerozoic

**Richard Hofmann, Melanie Tietje, Martin Aberhan**

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Biodiversity can be dissected into three components known as alpha-diversity (local species richness), beta-diversity (differential diversity between localities), and gamma-diversity (overall species richness of the observed system). Originally introduced during the 1960s in evolutionary ecology, this concept known as diversity partitioning received considerable attention by palaeobiologists. It has been proposed that the interplay of alpha-, beta-, and gamma-diversity can be used to infer processes underlying diversification. On larger spatial scales this approach enables to assess geographic selectivity in the assembly of the global diversity signal. On smaller scales of local habitats, diversity partitioning allows to infer the importance of biological factors such as predation and competition depending on the relative contribution of beta-, alpha- to gamma-diversity. For instance competitive exclusion fosters taxonomic differentiation in benthic ecosystems, which should be expressed as increasing beta-diversity.

We herein applied this concept on the scale of geological formations as representation of coeval, neighboring habitats. Occurrence-data of non-colonial benthic marine macroinvertebrates were obtained from the Palaeobiology-Database from each geological formation with at least 25 collections. These formational compilations were subsampled by randomly drawing 20 collections for 500 times. Average collection species richness (alpha), composite species richness (gamma-diversity) of the 20 collections and several measures for beta-diversity were calculated for each formation. Finally, all alpha- and beta-values were plotted against gamma-diversity.

Our analysis reveals a strong and consistent positive correlation between alpha and gamma-diversity throughout the Phanerozoic. This suggests that local species richness always contributes to overall diversity. Furthermore, there appears to be no perceivable limit for both. Increases in gamma-diversity only correspond to increases in beta-diversity at low levels of gamma. This is mostly realized during the Early to Mid-Palaeozoic. In other time intervals, beta-diversity levels off at high gamma-diversity. The Permian, the Cenozoic, and to a lesser extent the Silurian are characterized by a generally beta-neutral relationship, where beta is relatively high but largely indifferent across the whole range of gamma. These time intervals roughly correspond to Phanerozoic peaks in global biodiversity suggesting that there is an upper limit to faunal differentiation and that exceptionally high diversity can only be reached by further adding species to local communities but not by finer partitioning among marine habitats. These findings suggest that interspecific competition drives ecosystem differentiation and thus acquisition of biodiversity on local to regional scales.

Talk

## Dynamics of extinction and origination in the marine fossil record: an update

**Wolfgang Kiessling**, Adam Kocsis

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The Paleobiology Database (PBDB) has made it possible to reconstruct sampling-standardized biodiversity dynamics that do not suffer from a Pull-of-the-Recent effect. Earlier Phanerozoic-scale analyses based on the PBDB established that the Mesozoic-Cenozoic rise of marine diversity was more muted than established from previous range-based compendia, that mass extinctions do not stand out as distinct outliers, and that diversity dynamics are partly driven by diversity itself (Alroy et al. 2008, Science 321: 97; Alroy 2008, PNAS 105: 11536). These previous analyses were based on 11 myr long time intervals and genera.

Here we take advantage of the growth of the PBDB and our new analytical package for R (divDyn available at GitHub) to provide an update of previous insights using a stage-level biostratigraphic resolution (mean of 6 myr duration). We also compare genus and species level analyses.

Contrary to previous results, there is no significant trend in background turnover rates over time and there is no lag one cross-correlation between extinction rates and originations rates. Instead, origination rates tend to peak simultaneously and after a lag of three stages following extinctions. There is also no significant correlation between standing diversity and lagged extinction. These basic results are maintained at the species level. Our findings suggest that previous assertions of diversity-dependent dynamics were premature and partly governed by too coarse temporal resolutions and an insufficient consideration of the Signor-Lipps effect. Depending on exact procedure, two to three mass extinctions stand out as significant post-Cambrian outliers and the end-Permian and end-Triassic are always among them. The quest for the "best" estimate of biologically meaningful diversity dynamics across the Phanerozoic needs to be continued.

Talk

## Contrasting shallow and deeper water marine assemblages of the highly heterogeneous biota from the Late Triassic Cassian Formation, northern Italy

**Alexander Nützel**[1], Imelda M. Hausmann[1], Mike Reich[1], Vanessa Roden[2]

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Composition and diversity of fossil assemblages from the Late Triassic Cassian Formation (northern Italy, Dolomites) are highly heterogeneous. Autochthonous basin and parautochthonous shallow water assemblages are present as well as shallow water assemblages transported into basinal settings during deposition. Ongoing bulk sampling and quantitative analyses of basin assemblages revealed a relatively low diversity and a strong mollusc dominance consisting of gastropods, bivalves and scaphopods. This mollusc dominance forms a modern trait and is in contrast to many Palaeozoic assemblages as is a lack or rarity of articulate brachiopods. Among gastropods, higher clades (Apogastropoda: Caenogastropoda and Heterobranchia) are the dominant groups while Vetigastropoda are almost absent and Neritimorpha are only present with early juveniles. In some cases mathildoid gastropod species (Heterobranchia) yield the most abundant species, which is an anactualistic phenomenon because this group forms only a minor component of modern assemblages and is never dominant. Echinoderms are entirely disarticulated but yielded ossicles and elements of groups that were previously only known from the Palaeozoic (with few exceptions) such as ophiocistioids and proterocidarid sea urchins. It is possible that such marine basins served as refugia for Palaeozoic echinoderm holdovers. In comparison with basin assemblages, shallow water assemblages display a much higher diversity with a within-sample-diversity of up to 180 species. Mollusc and especially gastropod dominance is shared by basin and shallow water assemblages. However, the species composition differs entirely and especially the most abundant species are not the same as those in basin assemblages indicating high beta diversity for the Cassian Formation biota as whole. Generally, Vetigastropoda, Brachiopoda and reef builders (corals and sponges) play a greater role in the shallow water assemblages.

Talk

## Volcanism, redox conditions, and microbialite growth linked with the end-Permian mass extinction: Evidence from the Xiajiacao section (western Hubei Province), South China

**Yu Pei**[1,2], Zhong-Qiang Chen[2], Yuheng Fang[2], Stephen Kershaw[3], Siqi Wu[2], Mao Luo[4]

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A new Permian–Triassic boundary microbialite (PTBM) is described from the Xiajiacao section of western Hubei Province, South China. The new microbialite, 3.16 m thick, comprises a thin layer of stromatolite and a thick thrombolite unit. An irregular contactseparates the uppermost Permian skeletal packstone from the post-extinction stromatolite, but it is not yet possible to discriminate whether it was formed by submarine solution in the wake of ocean acidification or subaerial exposure due to regional regression, or a combination of both. The stromatolite shows "cabbage-like" morphology, and the thrombolite is characterized by centimetric clotted texture. Abundant columns of the microproblematica structure *Gakhumella*, coccoid-like spheroids, clumped spheroids, and hollow spheroids are recognized in both stromatolites and thrombolites and may have played an important role in accretion of the microbialites. Pyrite framboid analysis indicates that microbialites may have been affected by lower dysoxic to upper dysoxic conditions in the immediate aftermath of the Permian–Triassic extinction. Stratigraphic abundance of both high-temperature grains (β-quartz and glassy balls) peaked ~20 cm below the biotic extinction horizon, implying that either intensive volcanic eruption occurred only just prior to biotic extinction, or volcanism was still intensive during biotic extinction, but volcanic grains were not deposited in the Xiajiacao locality, likely due to the shallow, agitated environment caused by the regional regression. Overall, microbial bloom, indicated by the widespread PTBMs, seems to have been little affected by the contemporaneous volcanism.

**Keywords:** stromatolite; thrombolite; microbial bloom; Permian–Triassic boundary; felsic volcanism; framboidal pyrite

**Poster**

## A first Palaeozoic-type echinoderm group representative from the Mesozoic

**Mike Reich[1,2,3], Tanja R. Stegemann[4,2], Imelda M. Hausmann[1,2], Vanessa J. Roden[5], Alexander Nützel[1,2,3]**

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Ophiocistioids are small pentaradiate, free-moving globular echinoderms, related to sea urchins and sea cucumbers. Rare as fossils, and enigmatic in terms of their phylogenetic position, members of the Ophiocistioidea have been considered an exclusively Palaeozoic echinoderm group. Apart from articulated body fossils (Ordovician–Devonian), the fossil record of Ophiocistioidea is otherwise dependent on isolated microfossils (Silurian–Permian), mostly goniodonts, which are disarticulated elements of the masticatory apparatus.

The Late Triassic Cassian Fm. of Italy is regarded as one of the most important strata of early Mesozoic invertebrates, including all groups of extant echinoderms worldwide. Here we present a fossil assemblage from a locality near Misurina, South Tyrol, yielding various echinoderms, including a stem group echinoid representative and a new ophiocistioid (*Linguaserra* sp. nov.). The latter new taxon represents the first documented occurrence of a 'Palaeozoic' echinoderm group from Mesozoic strata but also establishes the stratigraphically youngest record of goniodonts in the world. This new record in the Late Triassic Cassian Fm. of Italy has novel implications for understanding the Permian–Triassic fossil record of echinoderms, and shifts existing paradigms that 'Palaeozoic' echinoderms are exclusively found in Palaeozoic strata.

**Talk**

## High diversity in the Triassic Cassian Formation

**Vanessa Julie Roden[1], Imelda M. Hausmann[2], Barbara Seuss[1], Alexander Nützel[2], Wolfgang Kiessling[1]**

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The Middle to Upper Triassic Cassian Formation (Dolomites, Northern Italy) is the most diverse early Mesozoic ecosystem worldwide. A compilation of taxa described from the Cassian Formation contains 1336 species after revision. The species richness is very high compared with other fossil lagerstätten known for their diversity. For example, 228 species are reported in the Early Cambrian Chengjiang biota, 280 from the Upper Carboniferous Mazon Creek fauna, 491 from the Eocene London Clay, 147 from the Lower Devonian Hunsrück Slate, a literature compilation of the Upper Carboniferous Finis Shale of Texas yields 332 species, and a total of 861 animal species is reported from the Upper Jurassic Solnhofen Formation. Although the Cassian Formation stands out in the fossil context, a much higher species richness is recorded in Recent tropical ecosystems. For example, a comprehensive survey in New Caledonia, south-west Pacific, yielded 2738 species of molluscs alone (P. Bouchet et al., 2002).

With gastropods comprising 70 % of mollusc species (53 % of all species), it is clear that aragonite preservation has a large impact on the diversity of the Cassian fauna. In general, fossil lagerstätten can yield highly diverse communities due to preservational effects. To assess the degree to which the Cassian diversity is driven by a lagerstätten effect, we compare the proportion of stratigraphic singletons among well-known lagerstätten (Chengjiang biota, Hunsrück Slate, Mazon Creek fauna, Solnhofen, London Clay). Among those, the Cassian Formation yields the lowest proportion of singleton genera (17%), and next to lowest proportion of singleton species (68%). The lagerstätten effect is therefore lower than in most other datasets. We consequently conclude that intensive taxonomic work and preservational bias are not the only factors contributing to the high diversity. Beyond the large area (at least 500 $km^2$) and variety of environments covered by the Cassian Formation, yielding a very high beta diversity (mean proportional dissimilarity of 0.94), as well as aragonite preservation, the favorable living conditions in this tropical reef-basin allowed a highly diverse fauna to flourish.

**Poster**

## Biodiversity of non-maniraptoran theropod dinosaurs during the Mesozoic in Asia

**Adun Samathi**

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In this review, non-maniraptoran theropod dinosaurs found in Asia including India subcontinent are summarized start with the basal neotheropods to non-maniraptoran coelurosaurians. The purpose of this work is to collect and summarize the theropod groups in Asia for best understand their evolution, diversification, and paleobiogeography.

Theropods in Asia first appeared in the Early Jurassic, they consist of coelophysoids and basal tetanurans. During the Middle Jurassic, Asia was roamed by large-bodied Metriacanthosaurids and basal tetanurans, a contrast to Europe and North America which dominated by megalosaurids and allosaurids. In the Late Jurassic, Asia was still dominated by metriacanthosaurids with one possible megalosaurid, whereas in Europe, the megalosaurids and metriacanthosaurids were present together. This suggests that the mega-carnivore faunal exchange occurred between Asia and Europe during the Late Jurassic. This assumption, however, depends on the position of the Chinese Middle Jurassic *Monolophosaurus* which some studies found it to be a basal tetanuran or to nest within Megalosauroidea, or Allosauroidea and the Chinese Middle Jurassic *Xuanhanosaurus* which some studies found it to belong to Metriacanthosauridae or Megalosauroidea. The metriacanthosaurids also migrated to Southeast Asia during the Late Jurassic. In the Early Cretaceous, theropod faunas in Asia much diverged than other time e.g. spinosaurids, carcharodontosaurids, basal ornithomimosaurs, basal tyrannosauroids, and megaraptorans were present. In the Late Cretaceous, Asia was the place of tyrannosaurids and ornithomimids, with a small number of non-tyrannosaurid tyrannosauroids and one report of carcharodontosaurid, whereas the India subcontinent was roamed by the abelisauroid ceratosaurs.

**Poster**

## Permian laminites – a key for palaeoenvironmental reconstruction

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Laminites are usually regarded as excellent climate archives even back in deep time.

Recent excavations in the Thuringian Forest Basin investigated the Wintersbrunnen lake horizon of Asselian/Sakmarian age at the Leinatal locality. There have been excavated a 16 m thick lake profile with fluvial red beds of the initial lake phase through the main lake stage to the silting up phase and the transition to alluvial wet red beds in the top. The lake horizon belongs to the last perennial lakes in central Europe which developed in a wet phase during a general aridization.

The focus of the field work and the documentation was set on the typisation and interpretation of the pelagic laminites. On the base of the distinction of 12 different types of laminae and their sequences, 10 laminite types were characterized. The laminites mainly consist of Couplets. The bright laminae are mainly carbonatic and deposited during the warmer and drier months with an increasing bio-chemical carbonate precipitation, while the dark organic-rich clayey laminae with single quartz grains up to 0,2 mm represents sedimentation during wetter months.

Assuming that a Couplet represents a seasonal deposition, they are interpreted as annually deposited sediment. A counting of the Couplets indicates a lifetime of the lake of ~4980 years. The laminae show bundles up to 7 to 11, which could possibly be related to sunspot cycles, phenomena as the quasiperiodic ENSO or monsoonal climate variability.

Another palaeoclimate archives are Permian woody plants from the Chemnitz-Basin, showing tree rings in cordaitaleans/ conifers, calamitaleans and medullosan seed ferns. Ring sequences reveal an annual rhythm because of strong seasonality resulting from fluctuation in water availability concerning wet and dry phases.

More information about the climatic situation during the lake development is given by the terrestrial fossil record found in the lake sediments. The flora is mainly dominated by mesophilous to xerophilous elements such as walchians and ferns, which typically appearing together in lake sediments and pointing to subhumid to semiarid conditions. The climate interpretation is well supported by the wet red beds of *Scoyenia* facies, surrounding the lake.

Different lines of evidence can be used for palaeoclimate reconstruction. For future research a statistical evaluation of the laminites is necessary and intended.

Talk

## The early radiation of ammonoids after the global Kellwasser Crisis in the Canning Basin (Frasnian-Famennian boundary, Western Australia)

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The global Kellwasser Crisis at the end of the Frasnian was one of the first order mass extinctions, which led to the complete extinction of abundant and widespread marine clades and ecosystems. It had an especially severe impact on ammonoids, with only a single species (*Phoenixites frechi*) surviving unharmed and blossoming in the basal Famennian of the western Prototethys realm.

In Australia, we have no proof of any ammonoids from right after the extinction event, until higher in the lower Famennian (Upper Devonian = UD II-C, *glabra prima* Zone, Becker & House 2009). Our study aims at a better understanding of how the post-Kellwasser radiation of ammonoids (from UD II-C to UD II-E) progressed in the Canning Basin. Therefore, we used morphometric analyses of conch ontogeny in combination with suture developments and ornament to revise the taxonomy of lower Famennian populations of the Canning Basin. The new morphometric data are compared with German type material in order to look for similarities and to examine potential palaeobiogeographical migration along the Prototethys.

A new tornoceratid genus consists of three new species and the German *"Falcitornoceras" korni*. It differs from typical falcitornoceratids in the lack of their characteristic, juvenile, falcate ribbing. The oxyconic *Oxytornoceras* n. sp., a regional index fossil of UD II-D, differs from German oxytornoceratids in the lack of varices and the shape of its external lobe. *Cheiloceras (Staffites)* n. sp. is an abundant species in the UD II-D of the Ant Hill section. It can be easily recognized by its relatively large shells and prominent, dorsolateral, straight to slightly concave, star-shaped varices. In general, the Cheiloceratidae and early Dimeroceratidae show more complexity of shell shape, especially with respect to evolute or involute coiling and whorl expansion rates, than previously recognized. Overall, cosmopolitan genera dominate. However, the level of species endemism is significant in the Canning Basin. Our study confirms that the analyses of ontogenetic morphometry is essential to refine ammonoid taxonomy and in order to retrieve a reliable database for studies on palaeobiogeography and regional versus global radiation patterns.

### References

Becker, R.T. & House, M.R. (2009): Devonian ammonoid biostratigraphy of the Canning Basin. – In: Playford, P.E., Hocking, R. & Cockbain, A.E. (Eds.): Devonian reef complexes of the Canning Basin, W.A. Geological Survey of Western Australia, Bulletin, **145**: 415-439.

# 10c,e) Bone histology and tetrapod locomotion – Part 1: Bone histology; – Part 2: Tetrapod locomotion

Talk

## Functional inference from along-track variation in Late Palaeozoic tetrapod trackways

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Axial flexibility in quadrupedal amphibians and reptiles may have an effect on the trackway patterns they produce: Lateral bending of the trunk can result in a considerable change in pace length, pace angulation, apparent trunk length and imprint orientation from step cycle to step cycle – despite a generally straight forward movement. Accordingly, evolutionary changes in trunk flexibility may be inferred from the comparison of long trackways produced by related trackmakers. In the Early Permian ichnofossil record from the Thuringian Forest, tetrapod trackways assigned to non-amniote reptiliomorph producers are relatively abundant. Especially the ichnotaxa *Ichniotherium sphaerodactylum* and *Amphisauropus kablikae*, that can be referred to diadectid and seymouriamorph producers respectively, are known from several long trackways that include seven or more step cycles and thus are feasible objects for the study of along-track variation. *Amphisauropus* trackways display a significantly larger (a) variance in imprint orientation and (b) proportional variance in the apparent trunk length than *Ichniotherium* trackways. This difference might be attributed to a more constrained amniote-like derived gait and posture in *Ichniotherium* trackmakers whereas *Amphisauropus* represents a more amphibian-like basal reptiliomorph state and a walking style marked by a high component of axial propulsion via lateral flexion of the trunk. Through comparison of reptiliomorph along-track variability to that of amphibian, reptilian an synapsid trackways from the Late Carboniferous and Early Permian a more complex picture arises, suggesting that the decrease in lateral flexibility and evolution towards are more constrained locomotion in the stem-group of amniotes was not irreversible and that, among others, body size was a controlling factor.

Talk

## New data on avian medullary bone – implications for the identification of homologous tissues in extinct archosaurs

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Apart from a few exceptionally preserved specimens, unambiguous indicators of sex in non-avian dinosaurs are usually lost during fossilization. Birds, which are the only living representatives of Dinosauria, possess a sex-specific bone tissue, i.e. medullary bone (MB) that is produced by females during the laying cycle and used as a source of calcium for the formation of the eggshell.

Based on microstructural and chemical criteria specific to MB, MB-like tissues have been recognized in specimens of non-avian dinosaurs, thereby hypothesized to be gravid females. Indeed, MB is commonly described as a highly vascularized and strictly woven, endosteal bone tissue. Few studies have investigated its skeletal distribution and limited sampling has spurred the common misconception that MB is mostly formed in long limb bones. MB is also defined by a unique molecular signature. Components of its matrix, such as keratan sulfate (KS), are considered to be specific markers of MB.

However, the current definition of MB mostly results from its study in domestic bird species that are not representative of bird diversity. Moreover, the presence of MB in some extinct species has been debated based on "unusual" anatomical locations of MB-like tissues. Finally, some avian pathological bone (PB) tissues meet the microstructural criteria of MB, thus casting doubt on previous observations of MB in the fossil record.

To better characterize MB and refine the set of criteria from which to evaluate purported MB tissue in fossil archosaurs, we studied this bone tissue in over 60 species representative of extant bird diversity. Using micro-computed tomography and histochemical techniques, we assess the skeletal distribution and evaluate the extent of microstructural and chemical variation of MB in Neornithes. Using similar techniques, we also studied bone pathologies in 19 bird species, in order to test the hypothesis that MB is chemically different from avian PB tissues.

We show that MB can be found in most skeletal elements. The anatomical location of purported MB in extinct archosaurs is thus an invalid criticism against the potential reproductive nature of these tissues. Moreover, our results indicate that the microstructure and the chemical composition of MB are uniform among Neognathes. However, some large paleognathes show a different microstructure, which may be indicative of the ancestral morphology of MB. Finally, our preliminarychemical analysesreveal that some avian PB tissues may contain KS. Thus, KS is not an adequate molecular marker for conclusively identifying MB in birds and extinct archosaurs.

**Talk**

## Bone histology and growth record of the first juvenile individuals of Plateosaurus engelhardti

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The Late Triassic prosauropod dinosaur *Plateosaurus engelhardti* is well known from several hundred individuals from different localities, at least three of which are mass accumulations, in the Late Norian Löwenstein-Formation and its stratigraphic equivalents across Central Europe. Bone histology and other ontogenetic indicators had shown that *Plateosaurus* shows a poor correlation between size and ontogenetic age, with small mature and large immature individuals co-occurring. Alternatively, this pattern could result from unrecognized taxic diversity. However, until recent discoveries from the *Plateosaurus* mass accumulation at Frick (Cantone Aargau, Switzerland), no small juveniles with a femur length <40 cm were known that would have allowed evaluating hypotheses of developmental plasticity vs. taxic diversity. The lack of juveniles also has been an obstacle for the study of the life history of *Plateosaurus* through bone histology, because the early growth record in adult individuals is entirely lost by remodeling and expansion of the medullary cavity. We here describe the bone histology of the juvenile *Plateosaurus* from Frick (femur length 23 cm to 43 cm) and compare it to adults from the same locality. As in the adults, the juvenile bones show mainly fibrolamellar tissue, thus growth was probably fast and only little remodeling had altered the primary bone yet. Histometric data, including lamina thickness, canal size, osteocyte size, and osteocyte density, were collected and interpreted. Although lines of arrested growth (LAGs), presumed to represent annual growth marks, appear to be missing in the cortex of some juvenile long bone samples, a minimum age for the juveniles is established by measuring the thickness of the cortex and extrapolating this measurement to the total diameter of the bone, resulting in ages of only a few years. The ontogenetic stage of the small individuals is consistent with the hypothesis that the material from Frick represents as single, developmentally plastic, species.

**Talk**

## Reconstruction of an ancestral amniote trackmaker based on trackway data, track-trackmaker correlation and phylogeny

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Trackway measures, such as pace angulation, pace length, stride length, gauge width, manus-pes distance (along track) and imprint orientation vary notably among amphibian, stem-amniote and early amniote tracks from Late Carboniferous to Early Permian deposits. Some of this variability can be attributed to evolutionary changes in trackmaker anatomy and locomotion style close to the origin of amniotes and may be explored through phylogenetic approaches following the assignment of certain track types to distinct producer groups. Based on trackway averages of various parameters measured for eight tetrapod ichnotaxa from the Early Permian of the Thuringian Forest Basin as well as two additional Late Carboniferous ichnotaxa we infer ancestral states for functionally controlled trackway measures by means of parsimony and maximum likelihood approaches under consideration of two alternative trackmaker phylogenies: (1) diadectomorphs as probable producers of Late Carboniferous to Early Permian *Ichniotherium* tracks formed the sistergroup to all amniotes; (2) they formed the sistergroup of more derived synapsids within Amniota.

According to our results the ancestral amniote trackmaker had a body size higher than the sampled amphibian and reptilian track producers but was smaller than diadectomorph and early synapsid trackmakers. Its tracks were characterized by higher pace angulations, somewhat narrower gauges and lower normalized stride lengths than those of its non-amniote predecessors, whereas neither the normalized distance between consecutive manual and pedal imprints nor the orientation of the pedal imprints appear to have changed much on the amniote stem. The manual imprints were more outward positioned and had a more parallel orientation than those made by earlier stem-amniote producers. Early Permian *Ichniotherium* trackways display certain similarities to contemporaneous synapsid tracks whereas other measures, most notably the orientation of manual and pedal imprints, differ considerably, demonstrating their limited use as model tracks of basal amniotes.

**Talk**

## Did Stereospondyli undergo metamorphosis? A mystery signal visible in histology of large temnospondyl humerus from the Rhaetian (late Triassic) of Bonenburg (Westphalia, Germany)

**Dorota Konietzko-Meier**[1,2], **P. Martin Sander**[1], **Tanja Wintrich**[1]

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Metamorphosis is the plesiomorphic condition for Lissamphibia, and many modern amphibians have biphasic life cycles. However the problem of how, where, and how many times metamorphosis emerged is still unresolved. Among non-lissamphibian Temnospondyli only in two clades, Dissorophoidea and Branchiosauridae, a substantial concentration of dramatic and rapid developmental events resembling the metamorphosis of modern amphibians is observed. In the histological framework of Lissamphibia, metamorphosis can be directly recorded as a thick line close to the medullary region. If present, metamorphosis as the most drastic event in the life history should be also recorded in the histology of Temnospondyli. Histological analysis of the midshaft of a large cyclotosaurid humerus from latest Triassic of Germany provides new information about life cycles of Temnospondyli. A regular pattern of alternating zones, annuli and lines of arrested growth (LAGs) breaks down after the tenth LAG, where a set of closely spaced growth marks consisting of dark lines is visible, with the last line more pronounced than the earlier ones. This set is followed again by three regular cycles consisting zones and annuli with double LAGs. In the very rare cases where the histology of long bones is known for fully adult Temnospondyli (i.e., *Apateon*, *Dutuitosaurus*, *Rhinesuchus*), double LAGs occur in outermost cortex independent of the postulated mode of life or size. Double LAGs are typical for the post-metamorphic cortex among Lissamphibian and reflect the seasonal deterioration of the environmental conditions, either climatic or nutritional, but also indirectly show the achievement of the post metamorphic stage of development. It is unclear if the double LAGs in these temnospondyls indeed indicate a late metamorphosis. However, the slow-down in growth in the *Cyclotosaurus* humerus occurring at an age of 10-12 years would be consistent with a gradual and late metamorphosis or attainment of sexual maturity. Thus the occurrence of regular double LAGs among Temnospondyli might then not only record seasonal deterioration of the environmental conditions, but also sexual maturity and the shift of energy investment from growth to reproduction.

**Talk**

## Inferring function from footprint shape in tridactyl dinosaurs

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The increasing record of fossil footprints has high potential for the understanding of dinosaur biology. Yet, results derived from the widely applied ichnotaxonomy tend to contribute little to the general picture of dinosaurs, especially in the case of bipedal, tridactyl dinosaur tracks. Here, we present statistical analyses carried out on a larger sample (n=303) of tridactyl theropod and ornithischian footprints from diverse geographical localities and time slots taken from the literature. We argue that footprint shape has less phylogenetic meaning than previously thought, but instead can provide valuable insights into functional morphology.

In theropods, one of the most variable features is the projection of digital impression III beyond those of II and IV. A strong digit III projection is found in modern, highly cursorial ratite birds, where only digit III is employed in propulsion, while digit IV is specialized in stabilization during running. Theropod footprints showing strong digit III projection and moderately splayed digital impressions thus may indicate cursoriality of the trackmaker taxon. Furthermore, a strong digit III projection is frequently associated with strongly reduced interdigital angles and elongated overall footprint shapes, especially in many footprints attributed to the ichnogenus *Grallator*. These features likely resulted in a more efficient locomotion, possibly in concert with an increased cursoriality, but also led to a diminished maneuverability.

Possible cursorial shape features are less abundant in ornithischian footprints. On the contrary, many of the larger footprints, especially those attributed to hadrosaurids, feature shapes wider than long, with low digital impression III projection values, much increased digital impression widths, and low interdigital angles. These shapes are consistent with a subunguligrade, columnar pes structure, and thus reflect increased graviportality. Theropod footprints lack comparable graviportal features even at body sizes, reflecting the need for varied motion in predatory dinosaurs.

Both theropod and ornithischian footprints frequently display very large interdigital angles in combination with narrow digital impressions. Such shapes, which are commonly found in birds, are likely incompatible with cursoriality as widely splayed digits increase the risk of over-extension, and thus injury potential, at higher speeds. They would, however, increase mediolateral stability, allowing for better support when walking on soft substrates or for weight reduction in the foot.

**Talk**

## Locomotion on limbs

**Holger Preuschoft**

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The origin of tetrapods from lobe-finned fishes is beyond doubt. The Devonian *Tiktaalik* has given reason to re-consider the basic conditions connected with locomotion on limbs. Elevation of the body stem from the ground evokes inside the body a particular pattern of bending moments and shearing forces. As soon as loads are not distributed evenly on the limbs of both sides, or if a stepping forward is attempted, there occur torsional moments. Aside from these “internal forces” in the body stem, a segmentation of the supporting limbs (into stylo- zygo- and autopodium) is more than suitable. Joints between the segments permit movements, but must be kept in equilibrium by muscles.

Obviously, all these “internal forces” must be sustained by the body structures: the skeleton sustains compressive forces, tensile forces are taken over by connective tissue, or, if the distances between skeletal insertions vary, musculature is required. Adapting lengths of muscles, however, costs energy, the rarest of all resources. Likewise, the amount of material must be as low as possible, to keep the mass, and its inertia (which resists being moved) on the lowest possible level. Location as well as shapes of the stress-resisting structures, which together determine the body shape of a vertebrate, can be predicted by theoretical mechanics.

Not only in “low tetrapods”, but also in evolutionary advanced and highly mobile forms, like birds and mammals, the analysis of statics shows how the generally valid theoretical conditions are fulfilled. Observed details of morphology can be taken as proofs for the correctness of the foregoing mechanical analysis. A really complete analysis, however, of especially the pelvic girdle, with adequate methods still is a demand for future research.

Extending the biomechanic analyses on the kinetics of moving bodies allows understanding of characteristic modes of locomotion. Locomotor behaviour is also recorded by foot tracks; actually the earliest documents of a true tetrapod are tracks from the Late Carboniferous. Tracks provide the basic and most simple information: whether locomotion is performed on four or on only two limbs, distribution of body weight on front- and hindlimbs, width of the track, the number of toes,.

The probably more “primitive” quadrupedal locomotion requires little efforts for maintaining “external equilibrium”, especially in sprawling limb postures with diagonal footfall sequence. Nevertheless, this safe mode of locomotion is given up by sauropods as well as the sometimes highly evolved (cursorial) mammals, which move their limbs on parasagittal planes on often very narrow gages. Connected with this deviation from the primitive pattern seems to be the “invention” of gaits involving the flexion and extension (rather than lateral flexion) of the trunk. Among animals which move on all fours a variety of gaits is realised (walk, tölt, trot, pace, bound, halfbound, canter, gallop), unfortunately complicated by the inadequate terminologies of many authors. The identification of gaits from tracks requires as a precondition at least some knowledge about the size and relative limb length of the trackmaker.

The easier to analyse bipedality occurs repeatedly during evolution in frogs, lizards, many dinosaurs; birds, kangaroos, rodents, and primates. This is due to generally valid mechanical conditions. It can be performed by striding, running or hopping, the latter two gaits being characterised by phases of aerial suspension, which increase the distances covered in each cycle. Arrangement of muscles and mass distribution within the limbs is a matter of mass inertia.

While body shape as a whole, as well as details of morphology can be derived from mechanics, the selection of gaits still offers unsolved problems: Why do large birds run and not hop? Why have some dinosaurs and the forerunners of birds and of mammals switched to a different pattern of moving their limbs in parasagittal planes, rather than in sprawling postures? Why did the ancestors of mammals develop the “asymmetric gaits” with +/- synchronous foreswings of limb pairs, combined with sagittal flexion and extension of the trunk?

**Poster**

## A comparison of different histological approaches for skeletochronological age determinations

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Biologists and palaeontologists have used conventional microtomised thin sections and petrographic ground sections to study the microscopic structure of bone for centuries. Among numerous other applications, both approaches constitute the methodological basis for the skeletochronological individual age determination. Skeletochronology studies the natural growth marks recorded in animal bone, some of which are believed to reflect annual cycles. Reliable age estimates provide the information required for the reconstruction of various life history traits such as longevity, age at maturity, growth rates, and growth strategies. For fossil taxa this can offer valuable insights into certain aspects of physiology and population ecology otherwise not accessible. For extant taxa it can yield the demographic data needed for the successful conservation and management of endangered species. Even though many studies have shown that the usage of skeletal growth marks can lead to meaningful age estimations for some taxa, this approach seems less suitable for others. In addition, the interpretation of growth marks can be difficult due to structural variability and/or remodelling and should be carried out with caution.

This study uses long bone samples (humeri and femora) from extant amphibians, reptiles, birds, and mammals of known age for the first direct histological comparison of ground sections and conventional thin sections, with special emphasis on the comparability of age estimates derived from both approaches. Before sampling for histology, each bone was µCT-scanned to find the most suitable sampling locality (site of the smallest dimensions of the medullary cavity). Each bone then was prepared in a way that each specimen yielded two opposing samples allowing for a direct comparison of the two approaches in order to determine whether the same number of growth marks can be revealed. Furthermore, the known age of the sampled specimens allows for an evaluation of the overall accuracy of growth-mark-based age determinations: does the visible number of growth marks actually agree with the known age of the individual? This study thus will have implications for the general interpretation of skeletochronological data and potentially can lead to methodological improvements in studying both extant and extinct organisms.

**Talk**

## Black beauties: histology and geochemistry of Iguanodon bernissartensis from the Early Cretaceous of Bernissart, Belgium

**Koen HW Stein**

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*Iguanodon bernissartensis* is an iconic herbivorous Early Cretaceous (±125 Ma) dinosaur, and was one of the first discovered. In 1878, a large number of more or less complete skeletons was found and exhumed from a coal mine near Bernissart, Belgium. The skeletons represent the largest find of its kind in Europe, and their morphology has been studied extensively. The animals were found in lacustrine sediments,among numerous fish specimens but also crocodiles and turtles. The lake formed in a sinkhole, which later also swallowed the sediments containing the fossils. Skin preservation is not uncommon in the iguanodons, and apart from distortion by crushing, the preservation of the bones is exquisite. Unfortunately, these natural treasures are threatened by decay of the pyrite which is ubiquitously present in the skeletons. Therefore continued action is needed to preserve them. Here I present results on the bone histology and geochemistryof the Bernissart iguanodons. Core samples were taken from16 individuals and processed into thin sections. The analytical approach most notably involved polarized light microscopy, µXRF and nano-infrared spectroscopy, to demonstrate the morphological preservation of the bony tissues, and presence of metal sulfides and silicates in the medullary cavity. Pyrite did thus not affect the bony tissues themselves, which allowed assessment of the growth of this iconic taxon.

**Talk**

## Comparison of Metoposaurus-bearing localities – how can paleohistology help us to understand fossil ecosystems

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Metoposaurids are included in the group of Stereospondyli, an extinct clade of temnospondyl amphibians. Their occurrence is limited to the Late Triassic and they are distributed worldwide. The most commonly used method in paleontology to gain information about the mode of life and the living environment is so far the morphological description and the link with the geological setting. Paleohistology however, is a modern method which –based on inner structure of the fossilized (bone) tissue– enables gaining new information about the animals' biology. Up to date, the best histologically studied taxon is *Metoposaurus krasiejowensis* from the Norian locality in Krasiejów, SE Poland. Humeri are the most solely examined bones and they show a variation in growth pattern (histotypes) even though, they resemble in one morphotype. It is highly probable, that the histological variation reflects the variation of the local environmental conditions. To test this a comparison within the Metoposauridae family is necessary. There, bones of *Metoposaurus maleriensis (India), Dutuitosaurus ouazzoui (Morocco), M. diagnosticus (Germany)* and *M. algarvensis* (Portugal) have been studied. The first results show, that on the histological level (organization of matrix) all taxa represent the same scheme and the common presence of parallel-fibred bone mixed with lamellar bone as well as similar organization of the vascular canals seems to be typical for all taxa independent of the locality and individual age. Between bones also the clear differences resulting from the individual age is observed as i.e. degree of remodeling or secondary originated porosity increase. However, the most important differences are visible on the level of growth pattern and origination of the growth marks. The most important factors are thickness of the zones and annuli and the presence of the Line of Arrested Growth (LAG). In *Metoposaurus krasiejowensis* two growth patterns has been observed (H1 represents an alternating growth; H2 represents a rapid growth) which are not connected to the bone size. The typical LAGs are not observed there either. *Dutuitosaurus* shows only one growth pattern with thick zones, thin annuli and annual LAGs occurrence. *Metoposaurus maleriensis* is the most interesting so far as it seems to represents both histotypes observed in *M. krasiejowensis* as an age-dependent system (small bones represent rapid growth, larger bones alternating growth). It comes out that for better understanding the intraspecific variation and especially a possible population diversification – other methods, e.g. geochemistry, need to be applied.

# 10d) Marine reptiles: a successful story in Mesozoic ecosystems

Poster

## Thalattosuchian remains from the late Aalenian Eisensandstein Formation of Baden-Württemberg, southwestern Germany

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The fossil record of marine reptiles from the Aalenian is globally poor. In Germany they are mostly limited to isolated and fragmentary remains, although at least one ichthyosaur, *Stenopterygius aaleniensis*, is known from a complete and articulated skeleton. The Aalenian thalattosuchian record has not yet been studied in detail, and a number of specimens are still undescribed. Among these unpublished fossils is cranial and postcranial material from the late Aalenian Eisensandstein Formation ("Dogger β") of Baden-Württemberg (SW Germany) that is housed at the Staatliches Museum für Naturkunde Stuttgart. Despite their fragmentary nature, this material can be attributed to both major thalattosuchian subclades, Teleosauroidea and Metriorhynchoidea. The teleosauroid material includes five incomplete rostra, one dorsal and two caudal vertebrae. Metriorhynchoids are represented by a fragmentary dentary and an isolated postorbital. Most specimens derive from localities in Aalen-Wasseralfingen and they are preserved in an iron oolite matrix. The same region yielded historical material of which some was described in the 1840s as *Glaphyrorhynchus aalensis*. These specimens, which were held in the collection of Graf zu Münster, appear to be lost and the validity of *Glaphyrorhynchus*, which was one of the first described thalattosuchians from Germany, cannot be confirmed. The material from the Eisensandstein Formation forms part of an ongoing project to describe the Aalenian thalattosuchian record of Germany. Although only fragments are preserved, their study enhances our knowledge of Thalattosuchia – particularly helping to close some stratigraphic gaps in their fossil record. Furthermore, the material offers new insight into the late Aalenian marine ecosystems.

Talk

## Marine vertebrates and recovery of life from the Permian-Triassic mass extinction

**Michael James Benton**

*University of Bristol, United Kingdom*

The Permian-Triassic mass extinction was devastating for life on land and in the sea, but it provided an opportunity for the establishment of new kinds of ecosystems. In the sea, there was an escalation as brachiopod-dominated faunas were replaced by those dominated by bivalves, gastropods, malacostracans, and echinoids. Neopterygian fishes were faster moving than their precursors, and new predators emerged, including marine reptiles. After the origin of the first marine reptiles, including ichthyosaurs and sauropterygians on the lepidosaurian side of the diapsids, and some archosaurian groups, the clades diversified fast in Olenekian and Anisian, occupying a range of niches, including unusual diets such as durophagy. In fact, the morphological and functional disparity of Triassic marine reptiles was never again equaled. The new evidence from Chinese Lagerstätten such as Panxian, Luoping, Xingyi, and Guangling is explored, as well as numerical approaches to macroevolution that reveal patterns and models.

Talk

## The use of taphonomy and biomechanics in understanding the paleobiology of the Ichthyosauria

**Jelle Heijne, P. Martin Sander**

*University of Bonn, Germany*

Originally, taphonomy was a descriptive science, attempting to understand the fossils and their mode of fossilization, but increasingly paleobiological information is drawn from taphonomic analyses. The taphonomy of the Ichthyosauria, a diverse group of marine reptiles that rapidly attained a cosmopolitan distribution in the Early Triassic and persisted to the early Late Cretaceous, is particularly interesting. Not only do ichthyosaurs have one of the largest sample sizes in amniote paleontology, but some specimens show remarkable preservation of both mineralized tissues and soft parts. This rich record is mostly due to the long history of research on the European localities, particularly the black shale Posidonienschiefer Formation. Thousands of articulated specimens provide evidence for viviparity, diet, appearance, and soft tissue. However, many aspects of ichthyosaur paleobiology, especially regarding locomotion, buoyancy control, and body mass, need to be revisited.

We use taphonomy for providing insights into the paleobiology of ichthyosaurs by observing the mode of carcass arrival on the sea floor ("landing mode") and carcass disarticulation patterns. Observed "landing modes" are lateral, dorsal, ventral, and anterior. The latter is generally combined with one of the three other modes. We propose that the anterior landing mode resulted from arrival of the carcass on the sea floor head-first at an angle, being caused by the heavy skull. Ichthyosaurs accordingly had an anteriorly placed center of mass.

Because ichthyosaurs were lung-breathing animals, they must have reached the water surface head-first to breathe. To achieve this, ichthyosaurs must have produced an opposite force, compensating for the anteriorly positioned center of mass. This opposite force was most likely provided by the tail fluke. Furthermore, the air-filled lungs might have aided in buoyancy control in the living animal during normal swimming. This aid was lost after death.

Ichthyosaur specimens that show the anterior landing mode can be recognized by broken snout regions, position of the skull at an angle to the bedding plane, heavily bent or disarticulated anterior vertebral column, and cervical vertebrae dislodged into the skull. Smaller individuals seem to lack anterior landing, though this might be caused by the lower impact momentum of a small or juvenile ichthyosaur compared to adult animals. Comparison with other marine tetrapods with both small and large skulls will show whether anterior landing is a unique feature of the Ichthyosauria or is found in a greater variety of marine animals.

**Talk**

## Spathian (Olenekian) bonebeds from Spitsbergen, Norway

**Jørn Harald Hurum, Hans Arne Nakrem**

*Natural History Museum, University of Oslo, Norway*

During the Early Triassic, the ocean that covered what was later to be known as Spitsbergen formed a part of a large embayment on the northern margin of Pangaea. Located in the northern regions of Panthalassa, the Boreal Ocean connected Eurasia/Baltica in the east with Laurentia/Gondwana in the west. The fossiliferous Early to Middle Triassic successions in Svalbard are some of the best, yet understudied localities to document and interpret the survival and recovery of marine ecosystems in the Boreal realm, with a crucial placement between Chinese and Nevada localities. During three seasons of fieldwork in 2014-16, abundant fossil material was recovered from the Lower and Middle Triassic Sassendalen Group (Vikinghøgda and Botneheia formations) in the Isfjorden area of central Spitsbergen. The excavations has focused on the Grippia and Lower Saurian bone beds, here preliminarily assigned to the lower and upper Spathian (upper Olenekian) respectively. The studies show a large diversity in the bonebeds with at least 17 species of chondrichthyians, several osteichthyes, trematosauroids, at least 3 different ichthyopterygians and an undetermined sauropterygian present. A rich fauna of conodonts is also present. Preliminary analysis has shown a slight taxonomic overlap of ichthyopterygian fauna between the two bone beds, at least at a generic level.

**Talk**

## Emergence and fast radiation of Mesozoic marine reptiles after the end-Permian Mass Extinction

**Dayong Jiang[1], Ryosuke Motani[2], Andrea Tintori[3], Jiandong Huang[4], Zuoyu Sun[1], Min Zhou[1]**

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Chaohu Fauna in Anhui Province has been known by yielding the geologically oldest basal ichthyopterygians such as *Chaohusaurus geishanensis* Young and Dong, 1972, with age of the Spathian of the Olenekian (Early Triassic). By the recent excavations, two aberrant basal ichthyosauriforms, two basal ichthyopterygians and one eosauropterygian were reported from the mid Spathian Upper Member of Nanlinghu Formation at Chaohu, among which *Sclerocormus parviceps* Jiang et al., 2016 is a large species of body length about 1.6 m, larger than coeval marine reptiles. Its sister taxon, *Cartorhynchus lenticarpus* Motani et al., 2015, is a small species but has a larger forelimb and shorter trunk. They were associated with the basal but possibly more pelagic ichthyopterygians *Chaohusaurus geishanensis* Young and Dong, 1972 *and C. chaoxianensis* (Chen, 1985), and eosauropterygian *Majiashanosaurus discocoracoidis* Jiang et al., 2014 from same level. It now appears that at least 26 marine reptile species occurred in the Middle-Late Spathian (in just 2 myr), amongst which 15 come from the South China Block. These include five hupehsuchians, two basal ichthyosauriforms, four basal ichthyopterygians, and four sauropterygians.

On the basis of ammonoid biostratigraphic analysis, the Milankovitch eccentric cycles revealed by the high-resolution record of carbonate carbon isotope and referred dating of Smithian-Spathian boundary, the age of the lowest stratigraphic level of Chaohu Fauna is 248.81 Ma, about 3.35 myr after the end-Permian mass extinction, and 1.35 myr after the Smithian-Spathian boundary. Furthermore, on the basis of high resolution stratigraphic record and morphological data, we found the evolutionary rate of Ichthyosauromorpha was fastest in the first two million years, six times faster than in Jurassic-Cretaceous, and became progressively slower over time. Applying the fast initial rate suggests that Ichthyosauromorpha emerged after the end-Permian mass extinction, matching an independent result from high-resolution stratigraphic confidence intervals. This demonstrates that marine reptiles underwent a fast radiation before the end of Early Triassic.

Poster

## Vertebral ossifications in fishes – key to the evolution of vertebral centra in amniotes?

**Ilja Kogan**[1,2], **Tanja Wintrich**[3]

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Although eponymous to vertebrates, the morphology and evolution of vertebrae and intervertebral discs is insufficiently researched. A survey of the fish outgroup is expected to provide insights into diversity and evolution of vertebral structures in order to better understand the mechanism of vertebral ossification in amniotes.

A persistent notochord surrounded by pairs of dorsal and ventral arcualia is the ancestral condition of the gnathostome axial skeleton. The acquisition of ossified vertebral centra occurred independently in several clades.

Vertebral centra can be either monospondylous or diplospondylous and constrict the notochord to various extents. In Osteichthyes, centra consist of several tissues or a combination thereof, namely arcocentrum, chordacentrum and autocentrum. Arcocentra are endochordal ossifications derived from the dorsal and vental arcualia, and can range from only slightly expanded neural and haemal arch bases to solid discs. Chordacentra result from mineralization within the fibrous sheath of the notochord and have the shape of rings or half-rings. Autocentra form as direct ossification of the elastica externa.

A few fossil actinopterygians outside the Neopterygii possessed ossified vertebral centra, which then usually were half-ring or ring-like, without any significant constriction of the notochord. Neopterygians exhibit a high diversity in vertebral design, from ossified centra lacking in pycnodonts to the possession of ophisthocoelous vertebrae in living ginglymodians, including various degrees of intravertebral notochord constriction. The presence of true autocentra seems to be an apomorphy of higher teleosts.

Ossified centra are absent in living sarcopterygians, but were developed in some Paleozoic dipnoans and osteolepiforms. Dipnoan vertebrae were amphicoelous, with a perforation for the constricted notochord; the vertebrae of osteolepiforms were half-rings or rings, always with a large notochordal space.

Evidence of ossified centra exists for a few placoderms, but not for acanthodians. Most neoselachian chondrichthyans have cartilaginous chordacentra, formed by migration of cartilage cells from the arcualia into the fibrous sheath of the notochord, and these can give rise to cartilaginous amphicoeolous centra.

The notochord of fishes can be incised to remain only in intervertebral spaces. A similar process happens during the development of mammals, where the incised residuals of the notochord form the nucleus pulposus. Likewise, incisions of the notochord occur at early ontogenetic stages of amphibians and reptiles. Based on this process and the morphology, it is hypothesized that some fossil reptiles show an intervertebral disc. Ontogeny, phylogeny and functional adaptations of fish vertebrae may therefore help understand the evolution of the vertebral column in amniotes.

Talk

## The earliest ichthyosaur from the middle Lower Triassic of Thailand

**Jun Liu**[1], **P. Martin Sander**[1], **Adun Samathi**[1], **Phornphen Chanthasit**[2]

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Biotic recovery from the Permian-Triassic mass extinction was accompanied by the invasion of the sea by several reptilian groups. Arguably the most important among these lineages is the ichthyosaurs. The ichthyosaur *Thaisaurus chonglakmanii* was discovered at a limestone hill in the Southern Peninsula of Thailand of putative Triassic age. Since its first brief description, however, *T. chonglakmanii* has never been restudied in detail and its exact stratigraphic and phylogenetic position remained elusive. Here we revisit the well prepared holotype specimen of *T. chonglakmanii*. The humerus of the holotype measures 21 mm long, suggesting a total body length of about 0.9 meter by extrapolation. This is even slightly smaller than the adult *Chaohusaurus* specimens from the Lower Triassic of South China, which was commonly taken as the smallest ichthyosaur before. Extensive cranial bone fusion and well-ossified limb bones, however, indicate an adult stage of the holotype specimen of *T. chonglakmanii*. Several characters suggest a much generalized morphology of *T. chonglakmanii* among ichthyosaurs, including notably the absence of the anterior terrace of upper temporal fenestra and an elongated humeral shaft without anterior flange. Parsimony analysis based on a published data matrix suggests the basal-most phylogenetic position of *T. chonglakmanii* among ichthyosaurs. Field reconnaissance combined with a published conodont study confirms a late Induan (Dienerian) – earliest Olenekian (early Smithian) age (*Sweetospathodus kummeli*-*Neospathodus waageni* zone) for the *Thaisaurus* locality, which corresponds well with the basal phylogenetic position of the taxon. This is the earliest record of Mesozoic marine reptiles, two million years earlier than the earliest previous record. Our result thus indicates that ichthyosaurs invaded the tropical waters at least as early as the Dienerian, when the sea surface temperature was relatively cool and the Refuge Zone was enlarged. The generally small body size of Early Triassic ichthyosaurs in the tropical oceans supports the inference of a stressed environment in the upper water column during most of the Early Triassic.

Poster

## A new Taphonomic Model for Brazilian Mesosaurs

**Heitor Sartorelli, Paul Martin Sander**

*University of Bonn, Germany*

Given their abundance and wide distribution, mesosaurs have been extensively studied under different perspectives. Taxonomically robust, comprising three well-established genera, as well as stratigraphically significant, such taxon plays a major role on the correlation between marine paleofaunas in African and South American coeval strata. Under a taphonomical point of view, however, little has been added to the study of these parareptiles. Despite possessing a wide-ranging dataset, the only current model for Brazilian mesosaur taphonomy depict some flaws based on incongruent interpretations. According to it, these organisms might have undergone an instant burrial after death, followed by successive storms that would have reworked previously deposited carcasses, generating different degrees of body disarticulation. Here I present a preliminary analysis showing an opposing perspective for this story: a long floating phase before residence at the water-sediment interface was indicated, as well as a more definite disarticulation pattern rather than randomly scattered events. The method employed here is based on a quantitative correlation between articulation and completeness levels in nine different parts of the skeleton, providing a basis for understanding trends in carcass disarticulation. On a broader sense, this is a good tool for elucidating some aspects of fossil deposition, such as transport in the water column, average time befote burrial or even disarticulation within the sediment. Additionally, a new approach on Brazilian mesosaur fossil assemblages might shed light on the depositional environment present at the African portion of the Whitehill-Irati Sea.

Talk

## Pachypleurosaurs from the Ducan area, Switzerland

**Marta S. Torres Ladeira, Torsten M. Scheyer, Heinz Furrer, Iris Ehrbar**

*Paläontologisches Institut und Museum der Universität Zürich, Switzerland*

Pachypleurosaurs are Middle Triassic marine reptiles known from the shallow waters around the margins of the Tethys Ocean. They are small, gracile animals with a slender body and long necks and tails. In Switzerland, pachypleurosaurs are predominantly known from Monte San Giorgio. The Middle Triassic of the Ducan region, near Davos, in canton Graubünden, constitutes a second fossil discovery site where pachypleurosaurs have been found. The first postcranial skeletal fragment was classified as the new species *Neusticosaurus staubi* by Kuhn-Schnyder; this classification is, however, uncertain, since the specimen is considered non-diagnostic at the species level. The new material collected in the Ducan region consists of six nearly complete specimens as well as isolated cranial and post cranial elements. The study of this material allows a reinvestigation on the species level classification of the pachypleurosaurs from this site, proposed to differ from the pachypleurosaurs known from Monte San Giorgio and other sites in Europe. Thus, we perform an interpretation about variation, sexual dimorphism and ontogeny; and the species *Neusticosaurus staubi* is analysed for validation. For this purpose, the new specimens are compared to the four species occurring in Monte San Giorgio, as well as to the pachypleurosaurs from the Middle Triassic of Germany and Netherlands. Several lines of evidence suggest that the investigated specimens are not known from other sites in Switzerland and Europe, thus no longer representing a *nomen dubium* or a junior synonym of *Neusticosaurus pusillus*. *Neusticosaurus staubi* might have had a common ancestor with the *Neusticosaurus* species from Monte San Giorgio. Specimens PIMUZ A/III 1275 and P96 are thought to represent a more gracile sex X, whereas the other, larger specimens are thought to represent sex Y. PIMUZ A/III 254, Kuhn-Schnyder's holotype, might be the smallest sexually mature specimen of sex Y in the sample, and PIMUZ A/III 711 is possibly a juvenile specimen.

Poster

## Pachystropheus rhaeticus: Osteological description of vertebrae from the Rhaetian of Bonenburg (Westphalia, Germany) and assignment to the Choristodera

**Anika Wild, Tanja Wintrich, Paul Martin Sander**

*University of Bonn, Germany*

During the Late Triassic (Rhaetian), a rich and unique fauna is recorded in the Rhaetic bone beds of western and Central Europe, including the famous Aust Cliff locality in the Bristol Channel area and newly discovered bonebeds in a clay pit in Bonenburg (City of Warburg, eastern Westphalia) in Germany. The Rhaetic bonebeds are highly time-averaged and sample a great diversity of habitats, from open marine to freshwater and terrestrial, and taxa ranging from chondrichthyans to possible dinosaurs and cynodont teeth. Rhaetic bone beds thus contain a remarkable amount of vertebrate diversity that provides insights for future research. The clay pit in Boneburg offers a great chance to expose the bone bed and study it in detail. During annual excavation campaigns since 2015, remains of the enigmatic *Pachystropheus rhaeticus* were by far the most common tetrapod remains. Amongst other skeletal parts, the characteristic vertebrae with a size range from 6 mm to 23 mm are most frequent. *Pachystropheus rhaeticus* is an extinct diapsid reptile that possibly represents the earliest member of the Choristodera. Bona fide choristoderes are Middle Jurassic in age, but the assignment of *Pachystropheus* to the clade would date its origin to the Late Triassic und would imply its survival of the Triassic-Jurassic mass extinction. While preservation as disarticulated elements impedes the skeletal reconstruction and phylogenetic classification, the abundance of the material somewhat compensates for this. In this study, over 100 vertebrae, mostly isolated centra but also some neural arches and complete vertebrae, from our excavations and from the private collection of Michael Mertens were studied. The vertebrae vary with body region in proportions, cross-sectional shape, and location of the rib articular facets. The centrum is in all body regions longer than high, which reflects the plesiomorphic condition in reptiles, but differs in the ratio of length to height. This ratio is highest in the cervical vertebrae and lowest in the sacrals, where the centrum is approximately 1.5 times as long as high. The dorsal vertebrae bear a broad neural arch with a distinct striation. Nearly all vertebrae show an open neurocentral suture, possibly indicating that only subadult individuals are represented. The neural canal is deeply incised with remant keels at the anterior and posterior ends, a feature associated to the Choristodera. Research on the skull elements, girdle, and appendicular skeleton could reveal further information on the phylogenetic affinities of *Pachystropheus rhaeticus* and its ecology.

**Talk**

## Soft part preservation in ichthyosaur vertebral column suggest a proper intervertebral disc

**Tanja Wintrich, P. Martin Sander**

*Steinmann Institut, Universität Bonn, Germany*

Ichthyosaurs represent one of the successful groups of marine reptiles which are known from the Early Triassic to the Late Cretaceous. Based on the morphology of the skeleton, ichthyosaurs were compared with dolphins and sharks, showing streamlined body shapes with a well formed fluke and flippers. All ichthyosaurs have deeply amphicoelous vertebral centra, but the notochordal foramen is vestigial if at all present. The morphology of ichthyosaur vertebral centra differs in shape and size, and centrum proportions change during the evolution from longer than high in the most basal taxa, the plesiomorphic condition in reptiles, to disk-shaped centra that may be twice as high as long, or more. The connective tissue in the intervertebral spaces of ichthyosaurs was thought to be similar to recent reptiles, which have a synovial intervertebral joint. To test this hypothesis, we investigated histological samples of an anterior dorsal vertebral column of the Jurassic ichthyosaur *Stenopterygius*. The specimen is a complete and only slightly disarticulated skeleton from the Toarcian Posidonienschiefer Formation of Holzmaden, Germany, that is famous for ichthyosaurs with skin impression. A segment of five articulated anterior dorsal vertebrae is of particular interest: the laminated sediment matrix encasing the specimen did not enter the intervertebral spaces. Instead, there are different types of matter that we interpret as altered intervertebral soft tissues. The bony articular surface is overlain by globular cartilage cells which, in turn, are overlain by dark, fine grained material which takes up the greater part of the intervertebral space. In the center of this dark matter, there is a round structure of translucent matter with a coarser fabric. We interpret the dark matter as altered fibrocartilage, representing the annulus fibrosus, and the central, round translucent structure as the altered nucleus pulposus. The coarse fabric probably reflects the much larger cells of notochordal origin that form the nucleus pulposus. The intervertebral spaces in the vertebral column of *Stenopterygius* were thus occupied by an intervertebral disk attached to the cartilaginous endplates of the vertebral centra. The end plates consisted of a layer of actively proliferating hyaline cartilage. The intervertebral ligaments or the joint capsule appears to have been weakly developed. Here we hypothesize that the preserved tissues represent a proper intervertebral disc of the kind seen in mammals with a nucleus pulposus surrounding by an annulus fibrosus.

**Talk**

## A bizarre, new ichthyosaur from the Blue Lias Formation (Lower Jurassic, Hettangian–Sinemurian) of the United Kingdom provides evidence for a temporally staggered ichthyosaur turnover across the Triassic–Jurassic boundary

**Andrzej Stefan Wolniewicz[1], Ryosuke Motani[2], Roger Bernard James Benson[1]**

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Ichthyosaurs were a long-lived and globally-distributed clade of Mesozoic marine reptiles. Their morphological and taxonomic diversity is thought to have been severely affected by the Triassic–Jurassic extinction event. Only one clade of ichthyosaurs, the Parvipelvia, is thought to have survived into the Early Jurassic, undergoing an adaptive radiation precisely at, or close to, the Triassic–Jurassic boundary. This hypothesis is supported by phylogenetic studies, which currently place all Jurassic and Cretaceous ichthyosaurs in the monophyletic clade Neoichthyosauria. Most of our knowledge of early neoichthyosaurian evolution comes from the Early Jurassic ichthyosaur fauna of the Lias Group of the United Kingdom. Lias Group ichthyosaur fossils are abundant, but the lack of extensive and detailed studies of their anatomy hinders our understanding of their true taxonomic diversity. Here, we report a new genus and species of ichthyosaur from the Blue Lias Formation (Lower Jurassic, Hettangian–Sinemurian) of the United Kingdom, based on two specimens comprising both cranial and postcranial material. The new taxon possesses three unambiguous autapomorphies and an unusual combination of anatomical characters, including ichthyosaurian plesiomorphies as well as features present in derived neoichthyosaurians. Plesiomorphies include the presence of the anterior terrace of the supratemporal fenestra and a posteroventral process of the jugal, and derived characters include the presence of a single foramen for the internal carotid artery in the basisphenoid. Phylogenetic analysis recovers the new taxon as an early-diverging parvipelvian outside of Neoichthyosauria. The phylogenetic position of the new taxon relative to the Late Triassic early-diverging parvipelvians *Macgowania janiceps* and *Hudsonelpidia brevirostris* provides evidence for the previously unrecognized survival of a basal parvipelvian lineage into the Early Jurassic and, together with other recent discoveries, suggests a temporally staggered pattern of turnover among ichthyosaur lineages across the Triassic–Jurassic boundary.

# 10f) Isotope analyses on calcareous and phosphatic fossils: Potentials and weaknesses

Talk

## Combined use of $^{18}O/^{16}O$ and $^{34}S/^{32}S$ in apatite to decipher the ecology of vertebrates

**Christophe Lécuyer**

*University of Lyon, France*

Reconstructing the living environment of extinct vertebrates has often been challenging due to the lack of direct environmental proxies. In addition to the well-known technique based on the analysis of $^{18}O/^{16}O$ ratios in apatite, a new sulfur isotope tracer has been applied to a collection of bone apatite samples representing a wide spectrum of the extant vertebrate diversity such as crocodiles, snakes, turtles, mammals, birds and lizards. We show that the combination of these two isotopic systems allows the living environment of all these vertebrates to be unambiguously distinguished between freshwater, seawater (aquatic *vs.* semi-aquatic) and terrestrial. The fish-to-tetrapod transition, which was followed later by terrestrialization, represented a major step in vertebrate evolution. The conquest of continents gave rise to a successful clade that today contains more than 30,000 tetrapod species. However, the aquatic environment of early tetrapods and the vertebrate fauna associated with them has remained elusive and highly debated. The $d^{18}O$–$d^{34}S$ approach reveals that some Devonian vertebrates, including early tetrapods, were euryhaline and inhabited transitional aquatic environments subject to high-magnitude, rapid changes in salinity, such as estuaries or deltas. Euryhalinity may have predisposed the early tetrapod clade to be able to face Late Devonian biotic crises and then successfully colonize terrestrial environments.

Talk

## Improved constraints on U-series open-system processes in fossil reef corals by combined Th/U, Pa/U and Ra/Th dating: A case study from Aqaba, Jordan

**Johanna Christina Obert**[1,2,5], **Denis Scholz**[2], **Thomas Felis**[3], **Jörg Lippold**[4], **Klaus Peter Jochum**[5], **Meinrat O. Andreae**[5,6]

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Fossil reef corals are often subject to diagenetic alteration of their U-series isotope system. These open-system processes can cause inaccurate $^{230}Th/U$ ages. The combined application of $^{230}Th/U$ and $^{231}Pa/U$ dating enables us to better identify and constrain the nature and timing of open-system processes. In addition, $^{226}Ra/^{230}Th$ isotope analyses can provide further insight into the more recent diagenetic history of a fossil coral. Here we present $^{230}Th/U$, $^{231}Pa/U$ as well as $^{226}Ra/^{230}Th$ isotope ratios from five fossil reef corals of Last Interglacial origin from the Gulf of Aqaba, Northern Red Sea. The results show clear evidence for open-system behaviour of the corals with strongly elevated $^{234}U/^{238}U$) activity ratios and U concentrations indicating post-depositional U addition.

Quantitative modelling of different open-system scenarios allows reproducing the trends in the isotope ratios. Two of the five corals were probably affected by two separate phases of U addition with different $^{234}U/^{238}U$) activity ratios values. The trends observed for two other corals can be explained by U addition followed by U loss. For these four corals, the timing of the modelled processes is remarkably similar and can be constrained to approx. 1 – 6 thousand years (ka) and 100 – 102 ka after coral growth respectively.

Based on the modelling results, we suggest that conventional $^{231}Pa/^{230}Th$ ages may provide the best estimate for the true age of these four corals, which range from 114.2 to 118.4 ka. This implies a late Last Interglacial time of deposition. For the fifth coral, the effects of open-system behaviour are less well constrainable, and the true age might be larger than the $^{231}Pa/^{230}Th$ age (ca. 114.5 ka).

The timing of the modelled open-system processes suggests that the early event of U addition was most likely associated with precipitation of secondary aragonite and potentially occurred during the lowering of sea level at the end of the Last Interglacial. The later open-system event can be described as U redistribution within the coral reef since some corals apparently lost U while others gained U. The timing of the second event is broadly consistent with the Bølling-Allerød interstadial, which was probably characterised by enhanced wetness in this typically arid region.

Talk

## Diagenesis screening of fossil fish-teeth: Limits of cathodoluminescence-microscopy

**Kevin Stevens**[1], **Katrin Hättig**[1,4], **Detlev Thies**[2], **Günter Schweigert**[3], **Jörg Mutterlose**[1]

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Fossil fish-teeth are often used for paleotemperature estimates via the stable oxygen isotope method. Fish teeth have been found to form close to stable oxygen isotopic equilibrium thereby providing reliable archives for paleoclimatic and/or paleoecological reconstructions. It

is generally assumed that hypermineralized tissues of teeth like enamel and enameloid are robust to diagenetic alteration. Tissues like bone and dentin, on the other hand, are easily altered due to their high primary contents of water and collagen. One potential method to check for diagenetic alteration of phosphatic tissues and to determine a pristine state is cathodoluminescence-microscopy (CLM).

We studied six fossil shark teeth (*Sphenodus nitidus*) from the Nusplingen Plattenkalk (upper Kimmeridgian, Upper Jurassic) of southwestern Germany for their diagenesis and stable oxygen isotope composition. These findings are compared to microscopic data (CLM, SEM) from modern shark teeth (*Lamiopsis temminckii*, *Hemipristis elongata*). The fossil shark teeth enameloid and dentin both show red/orange luminescence. Following the traditional interpretation of CL-patterns this would indicate diagenetic alteration of the fossil enameloid. The stable oxygen isotope and SEM data of the fossil teeth, however, indicate a well-preserved state. We found that enameloid of modern shark teeth also displays red/orange luminescence, while the dentin shows homogeneous blue CL. This suggests that this pattern represents a primary phenomenon of shark teeth biomineralization and that red/orange CL of enameloid does not necessarily indicate diagenetic alteration.

Our observations indicate that not only carbonate biominerals but also phosphate biominerals might display primary red/orange CL, which restricts the use of CLM as a diagenesis screening method. The potential of other diagenesis screening methods for phosphatic tissues and causes of the primary CL patterns of the teeth are explored.

**Talk**

## Were giant inoceramids chemosymbiotic bivalves? - A sclerochronological point of view

**Eric Otto Walliser, Bernd Reinhard Schöne**

*Institute of Geosciences, University of Mainz, Germany*

Inoceramids are an extinct group of bivalves that flourished during the Late Cretaceous. Their shells provide an excellent geochemical archive for paleoenvironmental research. However, $\delta^{13}C$ values of inoceramid shells are often more positive and $\delta^{18}O$ values more negative than those of coeval benthic organisms. Since little is known about the metabolism of these bivalves, the interpretation of the data still remains a challenging task. According to novel high-resolution sclerochronological data ($\delta^{13}C$, $\delta^{18}O$, REE, and microgrowth patterns) obtained from shells of the USA, Japan and Italy, the observed anomalous isotope patterns can be ascribed to vital effects related to a chemosymbiotic lifestyle. *Platyceramus platinus* from the USA exhibit REE patterns compatible with reducing conditions in the water during shell formation and $\delta^{13}C$ values that resemble the typical $^{13}C$-enriched signal of modern thioautotrophic bivalves. In the case of *Sphenoceramus* spp. from Japan, the ability to harbor sulfide oxidizing bacteria enabled this genus to colonize ecological niches around cold seeps. Under such conditions, the inoceramids became exposed to warm interstitial waters, which determined a negative shift in $\delta^{18}O$ values of the shells. A chemosymbiotic lifestyle, however, was not shared by all inoceramids as suggested by the near-equilibrium $\delta^{13}C$ and $\delta^{18}O$ values of *Inoceramus* sp. from the Scaglia Rossa limestones of Northern Italy.

**Talk**

## A critical examination of bulk sample and in situ oxygen isotope analyses from phosphatic marine microfossils

**Thomas Wotte[1], Christian B. Skovsted[2], Martin J. Whitehouse[3], Artem Kouchinsky[2]**

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Temperature is one of the key aspects controlling the activity and evolution of organisms. For modern marine invertebrates, the upper thermal limit is 38°C with local variations towards higher and lower temperatures. Information on marine paleo-temperatures is provided by oxygen isotope ($\delta^{18}O$) studies on various geo-materials, e.g. calcareous and phosphatic rocks and fossils or cherts. Going back in Earth history, and independent from the analyzed material, $\delta^{18}O$ becomes progressively depleted in $^{18}O$, which would coincide with a successive rise in seawater temperature to about 60°C in the Cambrian. Whether this trend reflects an artefact of secondary processes, changes in the seawater oxygen isotope composition, or effectively enhanced seawater surface temperatures is still under discussion. In order to constrain more accurately the temperature of ocean surface waters across geological time, we used secondary ion mass spectrometry (SIMS) to determine the primary oxygen isotope signal of seawater via in situ analysis of early–middle Cambrian phosphatic brachiopods and small shelly fossils. In the most pristine shells, $\delta^{18}O$ values vary between 16.5 and 17.8‰ and correspond to temperatures of 30.9 to 36.9°C (assuming an ice-free ocean). Diagenetic alteration could be excluded due to in-depth SEM and SEM-EDS investigations. Therefore, these data clearly indicate normal tropical to subtropical sea surface temperatures for the early and early middle Cambrian subequatorial regions and our data thus explicitly rebuts hypotheses requiring a change in seawater chemistry or an adaption of early organisms to considerably higher temperatures. On the other hand, and despite no indication for diagenetic alteration, some brachiopod shells and sclerites of small shelly fossils show extremely low $\delta^{18}O$ values corresponding to temperatures of 50 to 60°C or even higher. In the case of bulk analytical methods, such unexpectedly high ocean temperatures could be interpreted as an artefact of altered sample material unavoidably incorporated during the analyzing process. But, we used in situ oxygen isotope analyses which should minimize – if not entirely avoid – contamination of the primary oxygen isotope signal. Therefore, the generation of mixed $\delta^{18}O$ signals that integrate the isotopic composition of the primary seawater and any diagenetic alteration should be excluded. Here, we critically examine the potentials and weaknesses of bulk sample and in situ oxygen isotope analyses for reconstructing seawater temperatures through the early Earth history.

# 10g) Reconstructing the ecological roles of extinct organisms: functional morphology, phylogeny and ontogeny

Talk

## Macroecological patterns in Paleozoic ammonoids

**Pascal Abel, Kenneth de Baets, Manuel Steinbauer**

*Geozentrum Nordbayern, Germany*

One of the main advantages of paleontology over neontology is the possibility to analyse evolutionary and ecological patterns not only in deep time, but also over several stratigraphic boundaries. Particularly the analysis of paleobiogeographic patterns through time allow answering questions related to large-scale changes, unfeasible with recent data alone. A clade of organisms, which clearly predestines for this kind of studies are ammonoids, cephalopods of the Mesozoic and late Paleozoic with a usually single-coiled shell. Ammonoids are highly abundant in many marine strata of the Mesozoic and late Paleozoic and show high evolutionary rates as well, often easily visible in the interspecific variation of their shell morphology. This makes them not only interesting for evolutionary biology, but also for researching macroecological patterns and large-scale ecosystem changes.

Here we use a dataset containing over 25,000 occurrences of Paleozoic ammonoids to quantify macroecological patterns and their changes with time, focusing especially on shell morphology, ontogeny and dispersal parameters. Even though being several times at the brink of extinction, Paleozoic ammonoids achieved a high diversity comparable to Mesozoic forms, making them interesting model organisms.

Talk

## Exploring the limits of ammonoid morphospace

**Kenneth De Baets[1], Christian Klug[2], Dieter Korn[3]**

*[1]Friedrich-Alexander Universität Erlangen-Nürnberg, Erlangen, Germany; [2]Paläontologisches Institut und Museum, Universität Zürich, Switzerland; [3]Museum für Naturkunde, Berlin, Germany*

Several mass-occurrences of juvenile specimens of coiled ammonoids are known where subadults and adult specimens only occur in low numbers since the late Early Devonian. This separation of early and later life stages as well as their extreme ontogenetic size increase up to three orders of magnitude suggest that their position in food webs likely changed during ontogeny. The juveniles of these species display conch morphologies that differ fundamentally from the adult stages. If we compare the changes in conch morphology through ontogeny in the light of Pareto Optimality according to which the morphology of organisms would fill a polygon or polyhedron in morphospace, we found that juveniles often plot elsewhere in this morphospace than the conspecific adults. Data points close to one of the vorteces of the polyhedron indicate optimization for the corresponding task. Although shape is not a proof of function, it appears plausible that juvenile conchs were selected rather for compactness while adult conchs were positively selected for conch morphologies with improved hydrodynamic properties. This appears plausible because at small conch diameters, swimming movements will not suffice for effective translocation and a planktonic mode of life is likely. If post-mortem transport can be ruled out, such observations corroborate the idea that the ecological position of derived ammonoids markedly changed during their ontogeny contributing to ontogenetic segregation. Considering their high fecundity, the extinction of ammonoids might therefore have had a great impact on the structure of zooplankton communities and taxa feeding on them.

Talk

## Convergent evolution within malacostracan crustaceans, or how to transform a shrimp into a lobster

**Carolin Haug**

*LMU Munich, Germany*

The phenomenon of convergent evolution has become a prime ad hoc explanation in many modern-day evolutionary reconstructions. Yet, the concept itself is so far only weakly developed. Here I present a possible case of convergent evolution within malacostracan ("higher") crustaceans. Based on this example I aim at improving our understanding what convergence means and how patterns of character transformation can be effectively compared. Already some decades ago, Glaessner suggested a (simplified) three-step model for the evolution of decapod crustaceans: shrimp – lobster – crab. The step lobster – crab has been variously treated as an interesting case of convergence in the past with various occurrences of the crab-type morphology in various lineages. The shrimp – lobster transition on the other hand has not been extensively treated. The shrimp-type morphology appears to be plesiomorphic for Eumalacostraca, hence is also plesiomorphic in various lineages, not only Decapoda, but also Hoplocarida (mantis shrimps and relatives) and Peracarida (opossum shrimps, side swimmers, woodlice and relatives). Furthermore, modern mantis shrimps as an ingroup of Hoplocarida and, for example, cirolanid isopods as an ingroup of Peracarida have evolved a lobster-like morphology. I will summarise the order of character transformations along these three lineages and compare in how far these patterns are re-occurring in all three lineages. Based on this comparative approach, possible cases of correlations of morphological changes and ecological changes on the one hand and intrinsic preconditions ("constraints") on the other hand can be identified. In fact, besides these three lineages of modern day malacostracan crustaceans, additionally now extinct lineages have evolved at least partial lobster-type morphologies and provide additional examples for comparison.

**Poster**

## Fossil insect eggs in amber

**Marie K. Hörnig**[1], **Carolin Haug**[2], **Thilo Fischer**[3], **Joachim T. Haug**[2]

*[1]Universität Greifswald, Germany; [2]LMU München, Germany; [3]TU München, Germany*

Modern insects show an extremely wide range of different strategies for investments in their offspring. Most prominent examples are guarding of the offspring, provision of nutrition, or provision of shelter. Furthermore, investment in the offspring also includes morphological modifications of the egg surface or egg-associated structures, for example, egg packages of cockroaches (oothecae), flower-mimicking eggs of assassin bugs, or specifically and distinctly structured eggs of net-winged insects. The investigation of egg morphology can therefore provide hints to different aspects of parental investment and reproductive strategies. This can especially be helpful with regard to the investigation of behavioural aspects in fossil species, where a direct observation is not possible. Also for a reconstruction of the evolutionary changes of different reproductive strategies of arthropods in deep time, it can be useful to include findings regarding the egg morphology of different groups. Although most insect eggs are quite robust and should have a good preservational potential, fossilized eggs of arthropods are rarely described in the literature. Here, we present some examples of well preserved remains of eggs enclosed in amber. Some of them are enclosed together with the adult or the nymphs of the same species, even caught in the moment of hatching and now preserved as cases of 'frozen behaviour'. Such syninclusions allow correlating the eggs with a species or group directly, and thus help to identify further isolated remains of eggs. Therefore, they give a unique insight into the behavioural aspects of insect species that lived millions of years ago.

**Talk**

## Dental function, tooth morphology and occlusion in basal Triconodontidae

**Kai R. K. Jäger**[1], **Richard L. Cifelli**[2], **Thomas Martin**[1]

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Eutriconodonta are a monophyletic taxon of early-diverging crown Mammalia. Within Eutriconodonta, the family Triconodontidae is characterized by equal height of all three main molar cusps, which represents a derived condition. Most major hypotheses on their dental function and occlusion date back to the 20$^{th}$ century and have not been put to test since. We reexamined the basal Triconodontidae *Triconodon mordax* and *Priacodon fruitaensis* with micro-computed tomography (µCT), in order to examine tooth eruption, morphology and occlusion.

*Triconodon* shows an unusual eruption pattern of the m4. This ultimate molar is formed in a crypt on the medial side of the coronoid process, well above the tooth row. Our reexamination of multiple specimens suggest that this is a unique eruption pattern, unknown (and likely absent) outside of the Triconodontidae. A secondary increase in molar count could explain the unusual placement of the last molar. We can further confirm a sequential replacement pattern of the premolars in *Triconodon*, based on the µCT data. This is consistent with the phylogenetic position of the Eutriconodonta as early-diverging crown Mammalia.

The occlusion of *Priacodon fruitaensis* was analyzed with the Occlusal Fingerprint Analyser (OFA). Previously it had been assumed that the occlusion in Triconodontidae resembled that of the stem mammal *Morganucodon*, with lower molar central cusp a occluding in between B and A of the upper antagonist. Our results show that *Priacodon* had an embrasure occlusion with the primary cusp a occluding inbetween two upper molars. Based on these new results, we suggest that the embrasure occlusion, which is also seen among Gobiconodontidae and Amphilestidae ,was most likely a common feature of all Eutriconodonta.

At the beginning of the power stroke, the major cusps along the molar row came in contact in a rapid succession. This system required a high degree of precision for the molar row to be well aligned at the beginning of the chewing path, before the first dental contact.

Our results have proven the suitability of the OFA methods in testing existing hypotheses on occlusion and dental function of fossil taxa. The Triconodontidae exhibit previously unrecognized occlusal patterns, which are potentially linked to a shift to a more carnivorous diet.

**Talk**

## Fossil Replicants - Integrating Preserved and Theoretical Morphologies in Biomechanical Analyses

**Stephan Lautenschlager**[1], **Imran Rahman**[2]

*[1]University of Birmingham, Birmingham, United Kingdom; [2]Oxford University Museum of Natural History, Oxford, United Kingdom*

New methods in digital visualisation, reconstruction and computational biomechanical analysis have significantly transformed the way in which fossils can be studied in the past decade. Facilitated by the advent of new hard- and software tools, these techniques are now becoming routine techniques in vertebrate palaeontology. However, by their very nature vertebrate fossils are often incomplete, broken or distorted when they are found. Furthermore, the comparatively small sample size of most vertebrate taxa makes it difficult to account for effects of intraspecific variation, sexual dimorphism, ontogeny and allometry. This presents a significant problem for functional analysis of specific morphologies or anatomical structures and the respective comparability of biomechanical behaviour.

Here, a versatile solution to these problems is presented by integrating theoretical morphologies in biomechanical analyses and studies on form and function. Using digital modelling techniques a wide range of theoretical morphologies can be created, which can subsequently be subjected to biomechanical analyses to test the functional significance of morphological features. This approach not only permits the overcoming of limitations posed by the incompleteness of the fossil record and preservation, but can also increase sample size significantly. Comparing theoretical models with actually preserved vertebrate morphologies allows ground-truthing this approach and testing hypotheses on morphospace occupation and convergence.

Advantages, disadvantages and possibilities of this approach are outline and different studies using this approach are presented, demonstrating: (i) how differences in mandibular morphology promoted niche partitioning in therizinosaur dinosaurs; (ii) how efficiency in marine locomotion of ichthyosaurs increased through time and phylogeny; and (iii) how convergent cranial characters provided functional advantages for herbivorous archosaurs.

**Talk**

## Fossoriality and the origin of the turtle body plan

**Tyler Ranse Lyson**[1,3], **Stephan Lautenschlager**[2], **Bruce Rubidge**[3], **Gabriel Bever**[1,3,4]

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The phylogenetic origin of turtles and the evolutionary and developmental origin of the turtle body plan have been vigorously debated over the last century. Recent advances in molecular systematics, novel insights into comparative morphology, developmental genetics and embryology, and the discovery of critical stem fossil turtles have significantly advanced our understanding of these questions. Specifically, morphological, including fossils, and molecular data now suggest a diapsid origin of turtles and the discovery of several fossil stem turtles combined with extant developmental data now provide a cohesive evolutionary developmental model for the origin of the turtle shell. This model can now be set within an ecological context that includes a consideration of the early selective forces (ecological, behavioral, functional, etc.) that may have shaped the unusual turtle body plan, specifically 1) the anteroposteriorly broadening dorsal ribs and the earliest origin of the turtle shell and 2) the secondary closure of the cranial upper temporal fenestrae and the origin of the anapsid turtle skull. New fossil material from the oldest stem fossil turtle, *Eunotosaurus africanus* (middle Permian, 260mya), from the Karoo Basin of South Africa indicates the initiation of dorsal rib broadening was an adaptive response to fossoriality. Similar to extant fossorial taxa, the broad ribs of *Eunotosaurus* provide an intrinsically stable base on which to operate a powerful forelimb digging mechanism. Fossorial correlates are expressed throughout *Eunotosaurus'* skeleton, most of which are widely distributed along the turtle stem and into the crown clade, indicating the common ancestor of *Eunotosaurus* and modern turtles possessed a body plan significantly influenced by digging. We then tested the role fossoriality may have played in the secondary closure of the upper and lower temporal fenestrae in the skull. We analyzed digital Computed Tomography reconstructions of the *Eunotosaurus* skull using finite element analysis as a means to assess the distribution of mechanical forces in the dermatocranium under different morphological and functional contexts. Results indicate that fenestral closure reduces both compressional and tensional stresses under a model in which the head serves as a brace during forelimb digging. A similar reduction did not accompany fenestral closure when loading forces were dominated by the action of underlying adductor muscles. Combined, these data provide strong support for the hypothesis that fossoriality was an important influence in the early evolution of the turtle body plan, including the origin of the shell and anapsid skull.

Talk

## Computational fluid dynamics and its applications in palaeontology

**Imran Alexander Rahman**

*Oxford University Museum of Natural History, United Kingdom*

Inferring the life habits of ancient organisms from fossils is key for reconstructing ecosystems in deep time. The recent development and increasing availability of techniques for computer-aided visualization and analysis of fossil specimens has lent greater rigor to such work, as virtual modelling approaches enable analyses of functional morphology to be carried out within an explicit hypothesis-testing framework. One such method for palaeontological functional analysis is computational fluid dynamics (CFD). CFD is tool for simulating flows of fluids and their interaction with solid surfaces that is widely used in engineering. Equations describing the motion of fluids are solved numerically using a computer, and the results can be visualized as plots of fluid properties within the flow domain. Here, I will present case studies of CFD applied to fossil taxa, spanning a range of specimen sizes, taxonomic groups and geological ages. These case studies demonstrate the great potential of CFD for rigorously addressing long-standing functional hypotheses, making it more feasible than ever before to reconstruct the ecological roles of extinct organisms.

Poster

## Marine larvae in Cretaceous amber – important insight into the evolution of parasitic life habits of epicaridean isopods

**Mario Schädel[1], Vincent Perrichot[2], Joachim T. Haug[1,3]**

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Isopods – generally known as woodlice – are crustaceans which not only managed to establish a terrestrial lifestyle from primary marine ancestors, but also show a great diversity in numerous aquatic lineages. Isopods are found in all water depths, occurring in the deep sea as well as in freshwater. Ecologically they perform various functions, from decomposing dead plant matter to hyperparasitism. Fossil isopods are relatively rare and in most cases are not very informative from a paleoecological view. Non-compressed, three-dimensional fossils, at best from Konservat-Lagerstätten, provide more details and may provide deeper insights into the ecology via functional morphology. Even better comparable to modern forms are specimens preserved in amber. There are quite some records of terrestrial as well as very few marine isopods from amber deposits from all over the world. However, we present here new findings that make a special case. Most isopods have offspring very similar to the adults, yet the new specimens are true larvae. Additionally, they represent the so far oldest record of a lineage of obligate parasitic isopods with a complex life cycle. The specimens are larvae of Epicaridea. As their name suggests, adults are found on shrimps (and other crustaceans) on which they feed as adults. Compared to other parasitic isopods the larvae of epicarideans are very small and feed on a different organisms than their parents, namely on small copepod crustaceans. Their development including the host change involves three distinct larval stages. Our findings represent the last true larval stage that searches for the final host while being part of the plankton. With the help of fluorescence microscopy we were able to reveal delicate structures on the very small fossils (ca. 0.5 mm body length) down to single sensory setae. We compare the morphology of our fossils with the available information on modern forms as well as to the only other fossil record of epicaridean larvae. Our findings provide an exceptional glimpse on the “morphology through time” for this very special isopod group.

Talk

## Micro-computed tomography reveals head posture in Pleistocene rhinoceroses

**Rico Schellhorn**

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The head posture in extinct rhinoceros skulls is normally reconstructed with the shape of the occiput. The occiput is oriented backwards in rhinos with hanging skulls. These rhinos are grazers with the muzzle near the ground, like the extant white rhinoceros. Rhinos with a more horizontal head posture show a forward inclined occiput. An example for such browsing rhinos is the extant Javan rhinoceros. The usage of micro-computed tomography allows insight in internal skull structures. Within this study, the inner ear of rhinos was virtually reconstructed to show the head posture using the orientation of the lateral semicircular canal within the skull. The lateral semicircular canal is one of the three semicircular canals of the mammalian inner ear and it is assumed that the lateral canal is held horizontally during normal activity. This approach is applied to skull remains of the woolly rhinoceros (*Coelodonta antiquitatis*), as well as remains of *Stephanorhinus etruscus*. The woolly rhino is known from glacial periods of the Pleistocene, while *Stephanorhinus* is known from interglacial periods. Following the inner ear reconstructions and the orientation of the lateral semicircular canal within the skull, the head posture of the woolly rhino is reconstructed with a hanging skull, while *S. etruscus* had a more horizontally carried skull. The reconstructed downward inclined head posture in the woolly rhino is in accordance with a backward inclined occipital crest, teeth showing adaptations to a grass diet, preserved nasal horns showing an anterior abrasion from removing snow cover, and gut content showing a diet consisting of low browse plants. On the other hand, *S. etruscus* shows a reconstructed horizontal head posture and therefore an adaptation for a browsing diet. This is in accordance with the cheek teeth which are showing cingula. Cingula in rhinoceros cheek teeth are an adaptation to preferably feed on leaves. The approach of using the lateral semicircular canal of the inner ear to reconstruct the head posture was also applied to extant rhinos. With this method, the extant white rhino, a strict grazer, also shows a hanging skull like the grazing woolly rhino. According to the lateral semicircular canal orientation, the only strictly browsing extant rhino, the Javan rhino, shows a more horizontally carried skull like the browsing extinct *S. etruscus*.

**Poster**

## A terrestrial vertebrate fauna from the Lower Cretaceous (Barremian–Aptian) of Balve, Westphalia, Germany

**Achim H. Schwermann, Lothar Schöllmann, Christian Pott**

*LWL-Museum für Naturkunde, Germany*

The Sauerland area in the southern part of Westphalia is dominated by Devonian strata including reef limestones (‘Massenkalk’) that have been deposited in Middle to Upper Devonian. Although karst fissures and caves are not rare in the Sauerland, most of the pre-Pleistocene fillings are barren, but some are known to yield fossils. These latter, however, are very heterogeneous in their respective ages: examples include a Pliocene site near Eisborn, a spore-pollen assemblage dating another locality in the same region as Miocene, or a terrestrial filling at Brilon-Nehden, which is from the Lower Cretaceous.

The fissure filling of Balve yields both floral and faunal elements. The flora is so far restricted to fragments of charcoal and spore and pollen remains. Based on the latter, a Barremian–Aptian age is proposed for the filling. The faunal elements include mainly disarticulated bones and teeth of vertebrates with a high diversity: the record so far includes teeth, fin spines and head spines of hybodontiform chondrichthyans (Lonchidiidae); bones, teeth and scales of osteichthyans; and bone fragments and teeth of different amphibians (e.g. salamanders), small reptiles, turtles (*Helochelydra*?), crocodiles (Goniopholidae, Bernissartiidae, Atoposauridae), pterosaurs (Ornithocheiridae?), saurischian (Coelurosauria; Tyrannosauridea, Dromeosauridae) and ornithischian (Iguanodontia, Hypsilophodontidae, Ankylosauria) dinosaurs as well as teeth and jaw fragments of mammals (Dryolestoidea, Multituberculata, symmetrodont taxa).

A striking taphonomic filter significantly sorted the body of objects and excluded those larger than about a decimeter in size. The vertebrate remains consequently display a size from sub-millimeter range to several centimeters. Most bones are preserved as fragments only. Whereas the fossil record of the fissure filling at Balve is poor in quality, the quantity of the fossils and high taxonomic diversity is remarkable. A detailed systematic analysis will reveal faunal correlations with chronologically similar terrestrial fossil sites in Brilon-Nehden/Germany and Bernissart/Belgium, as well as the English Wealden, and with other European sites. The faunal diversity of the fossil content renders the Balve fissure filling an important component in the restoration of the Lower Cretaceous ecosystems of Western Europe and to explain palaeobiogeographic patterns in the Northern Hemisphere.

**Poster**

## Functional morphology of apodid body-wall ossicles (Echinodermata: Holothuroidea) from the Late Triassic Cassian Formation, Italy

**Tanja R. Stegemann[1,3], Mike Reich[2,3,4]**

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Body-wall ossicles of sea cucumbers (Echinodermata) play an important role in terms of functional morphology in apodid Holothuroidea. They are in charge of supporting locomotion within this group that is characterized primarily by lacking tube-feet, for example, by getting a better grip while burrowing or moving.

During a recently running bulk sampling of ~100 kg marly sediments we detected a diverse holothurian fauna representing apodid holothurians, in detail members of the Chiridotidae and Myriotrochidae. Overall, there is a large amount of micro- and mesofossils respectively microscopic remains of invertebrate and vertebrate macrofossils (especially molluscs) associated. Besides isolated „normal" holothurian hook ossicles (hook-like ossicles, sigmoids) of small sizes, which are well-known in Palaeozoic and Mesozoic strata, our new findings are in part unusual in terms of morphology and size. These are interpreted as a special kind of functional morphology, not described in fossil holothurians until now. In addition, we provide a comparison of Early Mesozoic and modern hook-bearing sea cucumbers.

The present study of micro- and mesofossils of the Late Triassic Cassian Fm. of South Tyrol, Italy, shows that this lagerstätte which is regarded as one of the most important strata of Early Mesozoic invertebrates worldwide is also a significant source for further research on phylogenetic studies in Holothuroidea in general.

**Talk**

## Geometric morphometrics and finite element analyses reveal the Haast's eagle (Harpagornis moorei) to be a mixed predator-scavenger

**Anneke H. van Heteren[1,2,3], Leah R. Tsang[4,5], Peter Ross[6], Justin A. Ledogar[4], Marie R.G. Attard[4,7], Diego Sustaita[8], Philip Clausen[6], Paul Scofield[9], Stephen Wroe[4], Gabriele Sansalone[4]**

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The extinct Haast's eagle (*Harpagornis moorei*) was 30-40% heavier than the largest extant eagle. There have been speculations about its evolutionary history and ecology, though there is still no consensus on its feeding behaviour. This study aims at understanding the evolution and ecology of *Harpagornis* by combining 3D geometric morphometrics and finite element analysis (FEA) on three-dimensional models constructed from CT-data of skulls and talons of Accipitridae.

Statistical analyses revealed the presence of two independent modules (beak and neurocranium) and of a strong allometric effect in the skull. Size-free shape analysis of the two modules revealed that *Harpagornis*' beak was similar to the eagles, while it's neurocranial morphology was more like a vulture. In most cranial FEA loading cases, there seems to be a dichotomy between Cathartidae on the one side and Accipitridae on the other. FEA on the skull, nevertheless, indicates that *Harpagornis* and the scavenging species of our dataset are well adapted to perform a pull-back motion.

The talon results suggest *Harpagornis* was an active hunter. *Harpagornis'* talon occupies a position in morphospace close to its closest living relative *Hieraaetus* (smallest extant eagle), suggesting a phylogenetic constraint on talon shape. However, FEA showed that the talon of *Harpagornis* undergoes similar stresses to that of other hunting raptors which rely on large-sized prey (e.g. *Aquila audax*).

Neurocranial morphology and FEA, however, clearly indicate a feeding behaviour more similar to vultures, possibly because of the large size of its prey (e.g., giant Moa). *Harpagornis*' neurocranial adaptation probably allowed a stronger and faster pull back motion to quickly remove large chunks of meat from the prey, similarly to vultures. Moreover, our results document a rapid evolutionary change, which might have allowed *Harpagornis* to exploit large sized prey. *Harpagornis moorei* therefore represents an extreme example of how freedom from competition in island ecosystems can rapidly influence morphological adaptation.

# 10h) Vertebrate jaws and teeth — form and function

Talk

## Functional modifications in tooth morphology of Paleocene small mammals

**Thomas Engler, Thomas Martin**
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The evolution of the tribosphenic molar is considered as major step for the evolutionary success of mammals. The development of the talonid basin at the lower molars, into with which the neomorphic protocone occludes like a pestle into a mortar, adds a crushing function to the plesiomorphic piercing and cutting. This functional modification made a wider range of diets accessible and increased the ecomorphological diversity of mammals after the Cretaceous-Paleogene extinction event.

An early modification of the tribosphenic molar with three main cusps is the addition of accessorial conules, such as para- and metaconulus. In several groups a fourth main cusp, the hypocone, evolved leading to a quadritubercular molar.

We have studied the functional changes from the plesiomorphic tribosphenic pattern to the quadritubercular condition in early Paleocene mammals from the Walbeck site in Germany and Porcupine Hill Formation of Canada. For a better understanding of the functional modifications, the molar patterns were classified in four morphotypes: triangular crown with small para- and metaconulus, without hypocone (**1**); triangular crown with small para-, metaconulus, and hypocone (**2**); quadrangular quadritubercular crown with large hypocone (**3**); quadrangular crown with large para-, metaconulus, and hypocone (**4**).

The masticatory cycle was virtually reconstructed with the occlusal fingerprint analyzer software, and the contact areas between antagonistic teeth were quantified for functional comparison. For the reconstruction of the chewing path three-dimensional surface models (µCT data) of the teeth and their wear facets including associated striations were used.

In all morphotypes a two-phased power stroke was reconstructed, which is typical for tribosphenic molars. During the masticatory movement, a change of direction and inclination of the lower jaw occurs between phase I and II. Compared to type **1** and **2**, in type **4** the size of para- and metaconulus is increased which leads to more bunodont tooth crowns. In mammals with this molar type, the directional change between phase I and II decreases (*Elpidophorus*, **4**). In quadrangular bunodont molars with a more even crown relief (*Prolouisina*, **3**), inclination decreases. In triangular tetracuspid molars (*Adapisorex*, **2**), the hypocone originates from the disto-lingual postprotocingulum. In this molar type, the hypocone occludes mesially along the paraconid into the trigonid basin and performs additional crushing, besides the protocone-talonid occlusion (**1**).

The observed differences in the masticatory cycle suggest differing dietary adaptations which will be studied using dental topographic analysis such as orientation patch count, relief index, and Dirichlet normal surface energy.

Grant: DFG-Project: MA1643/21-1

Poster

## Dietary Variation between Adult and Juvenile Cave Bears

**George William Harrison**
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Population dynamics in a species are important for understanding the factors controlling that species' population. Having juveniles and adults consume different diets is one common evolutionary strategy for increasing the carrying capacity of a species. Allowing juveniles to reach adulthood without directly competing with adults for food resources increases percent of juveniles that reach breeding age. Dietary reconstructions of individuals of different ages could reveal this interaction in fossil specimens.

One animal of particular interest is the extinct cave bear *Ursus spealeus*. Cave bears are a good target for these studies because the developmental patterns of their adult teeth are well studied. Furthermore, cave bears have a famously controversial diet, with dietary reconstructions based on functional morphology, nitrogen isotopes, and dental microwear of adult teeth giving wildly different results. One possible explanation is a shift in diet from an herbivorous diet when teeth and bones used in nitrogen studies are forming to a more omnivorous diet when dental microwear of adult teeth is formed.

This project analyzes dental microwear from adult and juvenile cave bears from Steinberg-Höhlenruine bei Hunas. The site is chosen due to its placement before the End Pleistocene, circumventing any possible dietary abnormalities related to food stress before the extinction of cave bears. Results will be compared with a dental microwear database (Goillot *et al.* 2009) to determine the diet of the cave bears. This study will use the previously established microwear techniques, generating a reference for future studies by other authors.

Poster

## Possible Crocodilian teeth from the lower Cretacious of North Rhine Westfalia

**Anna Lena Heika Kizner Zamudio**[1], **Achim Schwermann**[2], **Markus Bertling**[1]

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Seit 2002 wird unter der Leitung des LWL Museums für Naturkunde (Paläontologische Bodendenkmalpflege Westfalen) in dem Steinbruch Beckum im nördlichen Sauerland (Balve) gegraben. Seit dieser Zeit wurden unter Anderem große Mengen bisher unbestimmter Zähne, Panzerplatten- und Knochenfragmente gefunden. In dieser Arbeit sollen die Funde von mehreren Hunderten, bisher unbestimmten Zähnen und zweier Kieferfragmente behandelt werden. Diese stammen vermeintlich von der Ordnung Crocodilia, Familie der Goniopholididae und Atoposauridae (vermutet: Theriosuchus). Dazu werden die Fundstücke unter dem Mikroskop sowie dem Rasterelektronenmikroskop analysiert, vermessen und beschrieben. Die Stücke werden mit anderen bekannten Mitgliedern der Ordnung der Crocodilia sowie Saurischia (Unterordnung Theropoda) aus anderen, mit der Fundstelle assoziierten, geologischen Settings verglichen. Damit soll ein weiterer Ein- und Überblick in das hier ehemals bestehende Ökosystem und seine Lebewelt geboten und somit weiteres Wissen über die Unterkreide Deutschlands erschlossen werden.

ABSTRACT Since 2002 there has been an ongoing excavation under the direction of the LWL Museum of Natural History (paleontological preservation and care of field monuments, Westfalia) in the quarry Beckum in the northern region of the Sauerland (Balve). Since that time, among other things, large amounts of heretofore systematically undetermined teeth, armor plates and bone fragments were found. This work aims to analyze and determine the systematic status of several hundreds of these unidentified teeth as well as two jaw fragments from this excavation-site. They are suspected to originate from members of the order of Crocodilia; the family of Goniopholididae and Atoposauridae (specifically: Theriosuchus). The finds are analyzed, measured and described using the microscope and the scanning electron microscope. The pieces are compared with other known members of the Order of Crocodilia and Saurischia (specifically: the Suborder Theropoda) from other geological settings associated with the excavation site. This is to provide a further introduction and an overview of the formerly existing ecosystem and palaeoenvironment of, and thus further knowledge about, the Lower Cretaceous of Germany.

Talk

## Occlusal fingerprint analysis suggests complex oral processing in high-fiber herbivores since the Early Permian

**Philipp Ludwig Knaus**

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The development of high fiber herbivory is one of the key innovations among terrestrial vertebrates allowing large body sizes and shaping the structures of modern terrestrial ecosystems. Cenozoic terrestrial ecosystems have been mostly dominated by mammalian large high-fiber herbivores with a high diversity of tooth shapes and chewing apparatuses. Recently, several lineages of dinosaurs have been shown to also have developed mastication since the Cretaceous. However, the nature of oral processing outside Mammalia (including their closest relatives) and dinosaurs is recently understudied despite the presence of large tooth plates, wear facets, and elaborate skull adaptations for increased bite force in several suspected high-fiber herbivore lineages among Amniota and their sister group, the diadectids, since the Upper Carboniferous. Using occlusal fingerprint analysis, here I demonstrate distinct oral processing apparatuses in a Middle Triassic dicynodont (*Dinodontosaurus oliveirai*), an Upper Triassic rhynchosaur (*Hyperodapedon* sp.), and a Lower Permian diadectid (*Diadectes absitus*). Photogrammetric models were produced from skulls and mandibles using a Sony alpha 6000 camera and Agisoft Photoscan. The 3D-models were loaded into the software Occlusal Fingerprint Analyser. Informed by published and gathered data on the main orientation of dental microwear and constrained by the shape of jaw articulations, the main direction of movement was taken to produce possible paths of “mastication” in advanced mode of Photoscan. For the edentulous bite of *Dinodontosaurus* a reconstruction of the dicynodont rhamphotheca was produced in the 3D graphics software Blender to reconstruct the occlusion surface of the jaws. *Dinodontosaurus* was reconstructed to have a shearing bite with strong forces of lateral shearing being exercised on the bolus by medial ridges on the dentary and premaxillary as the lower jaw was retracted against the skull. The previously hypothesised orthal jaw movement of *Hyperodapedon* was confirmed with the mesial and distal parts of the maxillary dentition likely not occluding leading to a crushing-shearing bite due to the edged shape of the lower jaw. Preliminary analysis of *Diadectes* showed only a small contact patch on the broad teeth suggesting a mostly ripping and piercing mode of oral processing. The results demonstrate that complex oral mastication processes evolved independently in several terrestrial vertebrate lineages outside dinosaurs and mammals. Further candidates for complex oral processing and thus prospective subjects of further study might be captorhinid reptiles, bolosaurid parareptiles, and edaphosaurids.

Poster

## Morphological convergence and functional diversification of sabre-toothed vertebrates

**Stephan Lautenschlager**

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Sabre-toothed mammals, such as *Smilodon fatalis* from the Pleistocene of North America, represent one of the most iconic and instantly recognisable vertebrate fossils. Due to its unusual appearance, featuring two extremely elongated canine teeth, *Smilodon* has received considerable academic and public interest alike. However, sabre-tooths were much more diverse and abundant than this individual, well-known species would suggest. In fact, sabre-tooth morphologies have evolved at least seven times independently over the course of the last 250 million years: in Permian mammal-like reptiles known as gorgonopsians, in the marsupial sabre-tooth *Thylacosmilus*, and five different lineages of carnivorous mammals (including the family to which also modern large cats belong). This is a remarkable example for convergent evolution, which shows repeated appearances of a specific morphology in adaptation to certain environmental conditions, life styles or behaviours.

Due to this overall morphological similarity, it is generally assumed that the cranial function of sabre-toothed vertebrates is the same or largely comparable. Some differences between cat-like taxa with long, moderately flattened and finely serrated canines (dirk-toothed ecomorph) and taxa with shorter and broad, strongly flattened and coarsely serrated canines (scimitar-toothed ecomorph) have been recognised. However, despite these differences, it is assumed that they used a similar 'canine-shear' bite to drive their sabers through their prey. While this assumption has not been tested in detail from a biomechanical perspective, it is further unknown, if the same evolutionary trends led to the convergent emergence of sabre-toothed morphologies in different vertebrate groups.

Using a combination of digital visualisation, biomechanical analyses and evolutionary modelling, different functional performance measures were collected and compared across seven sabre-tooth groups. Absolute and effective jaw gape, bite force and mandibular stability and bending resistance were analysed for all taxa. The results demonstrate that these performance measures varied considerably between different groups and also between different species. Evolutionary pathways leading to the sabre-toothed morphology were further found to be significantly different between groups. This suggests, that functional diversity was much more widespread among sabre-toothed vertebrates than previously assumed and is likely related to differences in ecological niche occupation and phylogenetic constraints.

Talk

## Dental diversity and functional adaptations in Mesozoic mammaliaforms

**Thomas Martin[1], Julia A. Schultz[1], Janka J. Brinkkötter[1], Kai R. G. Jäger[1], Thorsten Plogschties[1], Achim H. Schwermann[2]**

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Mesozoic mammaliaforms exhibit a remarkable ecomorphological diversification which is reflected by their dental function. Dietary adaptations comprise insectivory, carnivory, piscivory, omnivory, and herbivory. The triconodont molariform type is the most plesiomorphic, with three cusps arranged in a longitudinal row. Jaw movement in triconodontans is orthal and the molars perform piercing and cutting. Dietary adaptations comprise insectivory in small taxa and carnivory in large such as *Repenomamus*. The next evolutionary step was triangulation of the molar main cusps with an arrangement of upper and lower molars forming alternating triangles, with an embrasure shearing occlusal type. This occlusal type is found in "symmetrodontans" and dryolestids and suggests an insectivorous diet. In dryolestids, a small single-cusped talonid is present at the posterior end of the lower molars. The chewing stroke is single-phased and comprises piercing and shear-cutting. In the subsequent evolutionary step, leading to the tribosphenic molar, the talonid was expanded and transformed into a basin. In the upper molars, the neomorphic protocone appears which occludes like a pestle into the talonid basin (mortar). The tribosphenic molar is characterized by a two-phased chewing stroke and adds crushing function to the piercing and cutting of the pretribosphenic condition of dryolestids. All modern mammalian (therian) molars are derived from the tribosphenic condition which first appears in the Middle Jurassic *(Juramaia)*. Convergently at least three times molars with a crushing and grinding function have evolved outside stem therians: in docodontans, australosphenidans, and Yinotheria *(Shuotherium)*. Docodontans have complex molars with various crushing structures and range from an insectivorous to omnivorous diet. Australosphenidans, on the stem line leading to monotremes (egg laying mammals), evolved convergently to tribosphenidans posteriorly oriented basined talonids, whereas in *Shuotherium* the talonid basin occurs on the anterior side of the lower molars. Both lack any traces of a protocone occluding into the talonid basin. A different adaptational molar type indicating omnivorous to herbivorous diet are the multicuspid molariforms of mammaliaform haramiyidans and crown mammalian multituberculates. While the jaw movement of haramiyidans is mostly orthal, multituberculates show a very efficient mode of chewing with a proal (anteriorly-posteriorly oriented) power stroke, analogous to muroid rodents. Rodent-like molariforms are also found in Cretaceous-Paleocene gondwanatherians of the southern continents that have rootless hypsodont cheek teeth with flat occlusal surfaces and enamel infoldings. In contrast to many stem mammals, most stem therians remained insectivorous until their explosive adaptive radiation after the K/Pg extinction event.

Talk

## Mandibular shape and chewing motions of Docodon victor

**Julia Ann Schultz**[1,2], **Bhart-Anjan Bhullar**[3], **Zhe-Xi Luo**[2]

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We re-examined dental and mandibular remains of *Docodon* from the Morrison Formation at Como Bluff, Wyoming USA (Late Jurassic), using Computed Tomography (CT) and 3D surface reconstruction. Our results support the long-held notion that the multiple species of *Docodon* of the same quarry are over-split. We formally propose that the specimens examined in this study should be synonymized under *Docodon victor*. Further on, the Occlusal Fingerprint Analyser is used to investigate the chewing motion of *Docodon*. The results indicate that the lower jaw moved palinally (backwards) in a distolingual directed chewing movement. The posterior directed movement of the lower jaw is functionally equivalent to the one reconstructed for unrelated traversodontid cynodonts, tritylodontids and multituberculates.

Two alternative historical interpretations of chewing motions in *Docodon* have been discussed previously: palinal and proal (forward). Our analysis shows large matching wear surfaces during occlusion and less shift in direction and inclination during the palinal movement. In comparison, the virtual reenactment of a proal chewing movement shows less matching contact areas for the same upper and lower molars and stronger deflections in the jaw trajectory during the movement out of occlusion after maximum intercuspation.

Our 3D reconstruction demonstrates that the peculiar mandibular shape of the holotype of *Docodon* (YPM-VP011826, Yale Peabody Museum collection), as previously illustrated, is mainly caused by the inaccurate restoration of tiny fractured pieces, that were manually glued back together. After identifying the correct positions of the pieces and virtually matching the fractures, the restored mandible of *Docodon* is very similar to better-preserved mandibles of other docodonts. Thus, mandibles of Late Jurassic docodonts varied far less than previously believed.

In addition, the material enabled us to trace ontogenetic changes of the Meckel's sulcus. In the youngest juvenile mandible available the Meckel's sulcus extends into the symphyseal region. In adult mandibles the sulcus retreats posteriorly, suggesting a change of the Meckel's element sitting in the sulcus during the ontogeny. The molar in the ultimate position erupts lingual to the coronoid in younger individuals, while the last molar of adult individuals erupts anterior to the base of the coronoid process. We interpret the medial ridge protuberance overhanging the postdentary trough to be the attachment site for M. temporalis profundus. The position of the ectotympanic notch on the posterior aspect of the mandibular angle indicates a different structural relationship of ectotympanic and mandible compared to those of other non-mammalian mammaliaforms.

Talk

## Wear, tear, and systematic repair: Testing growth dynamic models in euconodonts

**Bryan Shirley**[1], **Madleen Grohganz**[1], **Michel Bestmann**[2], **Emilia Jarochowska**[1]

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Conodonts are the first vertebrates to have developed mineralised, enamel-like tissues of unparalleled hardness, which resemble vertebrate tooth enamel structurally and in terms of functional adaptations. These dental tools are unique as they are able to repair both fractures and surface scores that occur during regular function. Euconodonts, the most derived group of conodonts, grew in a series of concentric layers deposited on the outer surface of the dental element. This allowed the elements to grow throughout the life of the animal. The reconstruction of conodont growth dynamics has been impeded by the difficulties in resolving individual growth layers (1 to 5 µm thick) in histological thin sections. We propose a different approach based on SEM imaging, which reveals the individual episodes of growth and allows for reconstruction of growth dynamics including episodes of *in vivo* repair. This, compiled with EDX measurements of chemical composition, can be used to define 3 stages of conodont ontogenetic development. We apply this approach to normally and pathologically developed specimens of *Ozarkodina confluens* in order to reveal the internal record of growth dynamics. Pathological growth and malformations combined with high resolution images of lamellar tissues can provide an insight into the mechanism of biomineralisation of these dental tools and reveal new histological features that have previously been unknown. Our findings support the model of periodic retraction of elements and addition of new growth centres. Changes in strontium content coincident with distinct morphology and lack of wear in the early life stage indicate that conodonts might have assumed their mature feeding habit of predators or scavengers after an initial larval stage characterised by a different feeding mode.

Talk

## First 3D enamel surface texture analysis of extant squamata and crocodylia

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Dietary reconstruction based on tooth morphology and wear has long focused on mammals (including hominids). In more recent years, dental wear analyses have expanded to non-mammalian vertebrates including dinosaurs, fish and conodonts. However, to establish a theoretical framework for feeding hypotheses and dietary inference for extinct taxa, reference datasets for extant species with known dietary habits are needed.

In this study, we have compiled the first extensive 3D surface texture dataset for extant non-avian sauropsida. 249 teeth from 17 extant squamatan taxa and 6 extant crocodilian taxa were analysed using a combination of roughness (ISO 25178), flatness (ISO 12781), furrow, and scale-sensitive fractal analysis (SSFA) surface texture parameters. Amongst squamates, faunivorous, herbivorous, frugivorous and durophagous taxa differed significantly in the furrow parameter *medf* and could be distinguished by several roughness parameters as well as the SSFA parameter *Asfc*. We found insectivores and omnivores to overlap, but these dietary groups were nonetheless separable by the height parameters *Sp* and *Sz* as well as in furrow parameter *medf*.

All extant crocodylians are faunivorous with few species showing dietary specialisations on hard prey or fish. More prey processing (tearing, slicing) is exhibited by large crocodylians, which suggests that their teeth frequently interact with bone. The smaller faunivorous squamata in our study mostly swallow their prey whole without further size reduction. While *Sz* in unspecialised faunivorous crocodylians resembles those of faunivorous squamates, the crocodylians display higher *Asfc* and *medf*. Overall, surface roughness and flatness are extremely variable in unspecialised faunivorous crocodylians. The saltwater crocodile (*Crocodylus porosus*), which is reported to include turtles in its diet, has the highest *Asfc*, *Sa*, *Sq* and flatness parameter values amongst crocodylia and resembles durophagous squamates. The piscivorous gharial (*Gavialis gangeticus*) displays very low surface roughness, height and flatness but high *medf*. Our results demonstrate that enamel surface texture analysis is a useful tool for dietary inference in extant squamates and crocodylians and has potential for comparison to assess feeding habits of extinct reptilian taxa.

Poster

## Cranial and mandibular morphology of Middle Pleistocene cave bears (Ursus deningeri): implications for diet and evolution

**<u>Anneke H. van Heteren</u>[1,2,3], Mikel Arlegi[4,5], Elena Santos[6,7,8], Juan-Luis Arsuaga[8,6], Asier Gómez-Olivencia[4,9,6]**

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Middle Pleistocene cave bear (*Ursus deningeri*) fossils are less common than Late Pleistocene cave bears (*Ursus spelaeus*) and, as such, they have been studied much less frequently. The objective of this contribution is to present, for the first time, an analysis of the cranial and mandibular shape of *U. deningeri* with regards to diet and evolution.

To do so, bear crania and mandibles were digitised with a Microscribe or CT-scanned and the surface models subsequently landmarked. Because many fossils were fragmentary, the landmarks were chosen based on a compromise between functional morphology and sample size. We used geometric morphometric analyses to quantify shape differences between species in the skull and the mandible. The potential influence of size on shape was also analysed. Prior to performing principal component analysis (PCA) and regression analysis, we performed a generalised Procrustes analysis on the raw coordinates to remove any information related to size, position and orientation. All analyses were performed in MorphoJ software.

Results show that Middle Pleistocene and Late Pleistocene cave bear mandibles display very similar morphologies and allometric trajectories, both to each other and to the herbivorous panda (*Ailuropoda melanoleuca*). From this, it is inferred that the masticatory adaptations to a herbivorous diet of the cave bear were already present in the Middle Pleistocene. The masticatory signal in the skull is less strong than in the mandible. Nevertheless, Middle Pleistocene cave bears display a cranial morphology that is different from both brown and Late Pleistocene cave bears, but more similar to the latter.

Finally, we observe that there are intraspecific differences between different populations of Middle Pleistocene cave bears, which could parallel the genetic diversity found in the Late Pleistocene cave bears. The intraspecific differences found within Middle Pleistocene cave bears may be temporal and/or geographical in nature and could be related to the evolution of the Late Pleistocene cave bear. This hypothesis should be further tested in the future with larger sample sizes of Middle Pleistocene bears.

# 10i) Greening of the living Earth: Advances in palaeobotany and palynology

**Talk**

## 'The smoking gun' – New evidence for Permian Corystosperms from Jordan

**Patrick Blomenkemper[1], Abdalla Abu Hamad[2], Hans Kerp[1], Benjamin Bomfleur[1]**

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The Late Permian Umm Irna Formation is a succession of up to 85 m of continental alluvial deposits exposed along the eastern flank of the Dead Sea, Jordan (Bandel and Khoury, 1981). It has yielded spectacularly well-preserved plant compressions with pristinely preserved cuticles, including the oldest occurrence of the corystospermalean seed-fern foliage *Dicroidium* (Kerp et al. 2006; Abu-Hamad et al., 2008). However, in the absence of fertile organs, the identification remained controversial (e.g. Pattemore et al., 2015). During recent fieldwork in 2017 and 2018, also the affiliated pollen organs (*Pteruchus*) and ovuliferous organs (*Umkomasia*) were collected together with a wealth of additional *Dicroidium* specimens and dispersed seeds. Cuticular analysis of the fertile structures enables a sound systematic placement, and offers the rare possibility to reconstruct foliage and fertile organs into a whole-plant species. The *Dicroidium* seed ferns were traditionally considered typical for the Triassic of south Gondwana; however, our results further add to the mounting evidence that these plants had a much stratigraphic and palaeogeographic range than previously thought (e.g. Shuqin, 2008; Shi et al. 2016). We are confident that continuing field work and research will eventually lead to additional whole-plant reconstructions for all occurring *Dicroidium* species, and contribute to a better understanding of how major plant fared during across the Permian-Triassic transition.

**Talk**

## Water lily leaves at the base of the Nuphar and Nymphaeaceae clades from the middle Eocene lake of Messel, Germany

**Carole T. Gee[1], David Winship Taylor[2]**

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Fossil leaves resembling those of *Nuphar*, known today as the pond lily or spatterdock, are rare in the fossil record. Yet, the remains of water lilies should be abundant in freshwater, Cenozoic lake deposits. A new look at some fossil leaves from the middle Eocene Messel lake deposits near Darmstadt, Germany, suggests that they may represent water lily foliage. Numerous leaves from historical and more recent collections were coded for their morphology and vein architecture using 55 characters, then analyzed phylogenetically using an extensive data set constructed with fossil and living taxa of the Nymphaeales and sister groups. The distinctive fossil leaves from Messel possess an elongate shape, peltate insertion of the petiole, a cordate base, a strong midrib, and extremely strong and regular secondary basal and lateral venation. In regard to the results of the phylogenetic analysis, the fossil leaves most commonly place at the base of the Nymphaeaceae, as sister to all members of the family. They place less often as the basal member of the *Nuphar* clade, as sister to derived Nymphaeaceae excluding *Nuphar* and *Victoria–Euyrale*, or as sister to derived Nymphaeaceae excluding *Nuphar*. In any case, these fossil leaves represent, in respect to their morphology and venation, the stem group of the Nymphaeaceae clade and may also be the oldest *Nuphar*-like leaves in the fossil record. Futhermore, they confirm the occurrence of the basal Nymphaeaeceae clade in freshwater lakes in Europe 47 million years ago.

**Talk**

## Prototaxites cf. loganii of the Rhenish Slate Mountains of W-Germany

**Rolf Gossmann[1], Peter Giesen[2], Markus Poschmann[3], Hans-Joachím Schweitzer †[1]**

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*Prototaxites* is a mysterious plant, which has given up riddles to palaeobotanists for almost 160 years after the first scientific processing by Dawson (1859). *Prototaxites* appears in Upper Silurian and vanishes from the fossil record at the end of Upper Devonian. The first specimens were discovered in the Lower Devonian of southeast Canada. As known, Dawson identified them as remains of fossil yews. Later botanical affiliation was changed to an alga, or a fungus or a tracheophyte.

In the Rhineland many silicified fossils were found, which seem to be identical to the Canadian fossils. The findings reach stratigraphically from Lochkovian to Zichovian. Fossils in Lower Devonian came from 21 quarries and other places in Taunus, Hunsrück, Eifel and from the Lahn River, as from numerous gravel pits in Tertiary or Quaternary sediments and in holocene river beds of Lower Devonian areas. In Germany *Prototaxites* seems to be restricted to Lower Devonian strata. That is one difference to American findings, which include Middle Devonian fossils. The other - more important - fact is, that the German fossils, embedded in rocks, all are coming from marine sediments or areas, which were situated at the coast of deltaic settings. The American findings were of terrestrial origin.

Very rarely the anatomical details of *Prototaxites* have been preserved during fossilization. In these cases roundish hyphes of nearly 0,03 mm width, smaller „hankhen hyphes" and broader dark "Markflecken" can be observed. These appear in longitudinal direction as short strokes. Different colored rings or semicircles are interpreted as growth zones, without them being explained in detail so far. Typically, the "stems" show cryptoxylon conservation, which means that the hyphes have been changed to small quartz crystals in the silicification process (Kidston, 1897, published *Prototaxites* remains as *Cryptoxylon forfarense*). *Prototaxites* usually occurs unbranched, but also a divided "stem" from the Hunsrück and parts of "stems" with branch remains from the Cologne area und the lower Rhine River are known.

Recently *Prototaxites* came into view of palaeobotanists again thru old and new hypotheses. Hueber (2001) consider these fossils as land-inhabiting giant mushrooms, but their basidiospores could not be identified until now. The possibility of a plant symbiosis or a mushroom is unlikely, because there is no convincing explanation how this large biomass was formed without extensive photosynthesis, if in their environment only small psilophytes lived. Hence, the most probable interpretation of *Prototaxites* is still that of a big seaweed.

**Talk**

## A new species of Plenasium (Osmundaceae) from the Eocene of Southeast Asia

**Philipp Hiller[1], Madelaine Böhme[2], Jerome Prieto[3], Simon Schneider[4], Benjamin Bomfleur[1]**

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Osmundales (The Royal Fern order) has a rich and diverse fossil record dating back into the Permian. Of special importance are their permineralized trunks and rhizomes, whose complex anatomical structure enables precise systematic placement. A particularly interesting taxon of fossil osmundalean stems is *Aurealcaulis*, a genus of hitherto unknown affinity that comprises large stems with an unusual, highly dissected stele that have so far been known only from the Cretaceous and Palaeogene of North America. Here, we present the results of a systematic analysis of calcified *Aurealcaulis*-like osmundalean stems from the Eocene Na Duong Formation (late Bartonian–Priabonian) of northern Vietnam. The trunk fragments are up to 1 m long, simple or branching, and exceed 20 cm in diameter. Each contains a central, up to 2-cm-thick stem that is clothed in a mantle of persistent stipe bases. The pith is poorly preserved, and mostly deformed or replaced by calcite spherules. The surrounding xylem siphon is very thick (up to 20+ cells in radial thickness) and perforated by abundant, complete leaf gaps into up to 25+ narrow segments. The cortex is two-layered with a thin parenchymatic inner layer and a thicker, presumably sclerenchymatic outer layer whose preservation is poor again due to growth of calcite spherules. The stipe bases bear a heterogeneous sclerenchyma cylinder with an outer ring of thick-walled cells and lateral wings containing several scattered fibre masses. Leaf traces originate from two protoxylem poles in two adjacent xylem segments, and depart from the stele in the form of two separate masses that fuse into an endarch, C-shaped trace in the cortex—a diagnostic feature unique to *Aurealcaulis*. Phylogenetic network analyses combining fossil and extant taxa identify this new species as intermediate between *Aurealcaulis* and extant *Plenasium*, supporting a recent assumption that *Aureacaulis* may in fact be an extinct subgenus of *Plenasium*. Moreover, this new species is not only the youngest known fossil record of *Aurealcaulis*, but also the first such stem that lies within the modern range of distribution of *Plenasium* today. Hence, this remarkable new species provides novel insights into the evolutionary history of modern Royal Ferns in terms of biogeography, geochronology, and anatomical structure.

**Talk**

## Revisiting energy yield patterns in the digestion of Araucaria and Equisetum by herbivores: Additional implications for sauropod food choices

**Mariah M. Howell[1], Carole T. Gee[1], Jürgen Hummel[2]**

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Before the advent of the angiosperms in the Late Cretaceous, Mesozoic herbivores of the Triassic and Jurassic, including sauropod dinosaurs, must have relied upon gymnosperms and ferns for sustenance. Among others, the dominant plant groups in this time included the conifer genus *Araucaria* and the horsetail genus *Equisetum*, both of which survive today. However, the nutritional content of these pre-angiosperm flora, and thus their ability to energetically support large herbivores, has long been underestimated. Here we present additional data that further supports previous conclusions that the energetic value of such flora can be substantial, with *Araucaria* and *Equisetum* both ranking highly as a function of gut retention time. Using the Hohenheim feed evaluation test to gauge energetic content and digestibility of living relatives of these Mesozoic plants has revealed that some taxa within these genera rival or even surpass angiosperms as food sources. Furthermore, consideration is given to the wide variation in nutritional quality among plants within the same family, genus, or even species and the potential influence of habitat. These results will be discussed in the framework of sauropod feeding and nutrition.

Talk

## A coal ball flora from the Hauptflöz Seam (Namurian C, lower Bashkirian, Pennsylvanian) of the Ruhr District, Germany

**Hans Kerp, Iryna Röhr**

*Westfälische Wilhelms-Universität Münster, Germany*

Coal balls are not only an excellent source of information on the anatomy and histology of fossil plants but they also give an insight in composition of the swamp-forest vegetation that accumulated the biomass that was eventually transformed into coal. Many coal ball occurrences have been described from North American coal basins, ranging from the Kanawha (upper Westphalian B, Duckmantian) in the Appalachians to the uppermost Pennsylvanian (Gzhelian) of the Western Interior. In western and central Europe, however, coal ball occurrences are fewer and mostly restricted to relatively few seams in the Westphalian A and B (Langsettian and Duckmantian) and a single older occurrence with a rather high number of endemic species in the Koksflöz Seam (upper Namurian A, Serpukhovian) in the Ostrava-Karvina Basin (Czech Republic). Most of the European coal ball floras were described from the 1870s to 1930s.

Here we present a coal ball flora from the Hauptflöz Seam, Namurian C, from the former Carl Funke Mine in Essen-Heisingen. Over 200 coal ball slabs were acquired for the Münster palaeobotany collection in the late 1960s. The collection originally probably consisted of around a dozen coal balls. Altogether some 25 taxa could be identified. The preservation varies from rather poor to excellent. Calamitaleans are the most common elements and are represented by roots (*Astromyelon*), stems (*Arthropitys*), strobili (*Calamostachys*) and leaves. Also well represented are ferns, especially *Stauropteris*; less common are *Botryopteris*, *Etapteris* and *Ankyropteris*. Lycopsids are not common and primarily represented by *Stigmaria* appendices, although these seem to be restricted to particular coal balls. Among the most common lycopsids are furthermore isolated *Lepidophloios* leaf cushions and leaves. Only few, rather poorly preserved lycopsid stems, *Lepidocarpon* megasporophylls and few cone remains were found. A partly decayed *Lepidophloios* stem is overgrown by a dense *Stauropteris* stand. The pteridosperms of the Häuptflöz Seam include *Medullosa*, *Lyginopteris* and *Heterangium*. Together with the silicified but rather poorly preserved plants from the same coal seam from a nearby mine described in the 1950s, the flora of the Hauptflöz Seam gives an idea of the composition of the swamp vegetation in the Yeadonian (early Bashkirian). The flora of the Hauptflöz Seam shows is comparable to those of the younger, Langsettian and Duckmantian coal ball floras from the Netherlands and Belgium. In contrast to these younger coal ball floras, the Hauptflöz flora is not dominated by lycopsids but by calamitaleans and to a lesser extent by ferns.

Talk

## Primary producers in the Lower Devonian Rhynie and Windyfield cherts: Cyanobacteria and eukaryotic microalgae

**Michael Krings[1,2,3], Carla J. Harper[1,2,3]**

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The Lower Devonian Rhynie and Windyfield cherts from Aberdeenshire, Scotland, have long been recognized as important rock deposits yielding comprehensive information on early continental plant, animal, and microbial life. Cyanobacteria and microscopic algae were no doubt pivotal as primary producers in the Rhynie/Windyfield ecosystem, and therefore must have been diverse and occurred in large quantities. However, only a few of these life forms have been documented in detail, due in part to the simple fact that specimens are often exceedingly small, and thus not readily recognized and studied. Moreover, the classification of cyanobacteria and microscopic algae today largely relies on molecular data and (ultra)structural features that are difficult, if not impossible to obtain from fossils. This presentation briefly reviews the documented evidence of primary producers from the Rhynie and Windyfield cherts, and presents several new discoveries of coccoid and filamentous cyanobacteria, including forms resembling the extant *Anabaena*, *Aphanothece*, *Cyanosarcina*, *Gloeocapsa*, *Merismopedia* and *Oscillatoria*, as well as sarcinoid and filamentous eukaryotic algae that are morphologically similar to present-day *Apatococcus/Desmococcus, Characium*, and *Ulothrix*. There is increasing evidence to suggest that some of these organisms became preserved only because they occurred in special micro-environmental settings that had a cushioning effect on destructive mechanical forces such as water movement, and thus functioned as microscopic conservation traps for delicate microbial life.

Talk

## Capturing fossil plants with photogrammetry: Case studies from the field and in the lab

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Digital data capture is a technological innovation fully entrenched in modern-day life, from barcode recognition at grocery stores to the scanning of the entire body in human medicine. In paleontology, break-throughs have been made in recent years in digital image capture and photogrammetric processing, which allow for the documenting, archiving, and reconstructing of fossils. Photogrammetry, a method that generates three-dimensional (3D) computer models from digital photos, has become increasingly applied in vertebrate paleontology. It is both nondestructive and easily applicable to the demands of paleontological field, lab, and collection work. Yet, its application in paleobotany has so far been restricted to a handful of simple uses. Here we show the high potential of photogrammetry for the documentation and analysis of fossil plants. To this end, we have digitized three paleobotanical objects using photogrammetry: two large, immovable tree trunks in the field and a fist-sized, fossil conifer cone in the lab. All three paleobotanical objects were "captured" in a series of digital images taken with a conventional single-lens reflex camera and processed into a 3D model using the photogrammetric software Agisoft PhotoScan. The first case study is a 150 million year old log (15 m long) at the Escalante Fossil Forest State Park in the Upper Jurassic Morrison Formation of Utah. The second example is a large, 17 million year old tree trunk rooted in original growth position in the Lesvos Petrified Forest in the Miocene of Lesvos, Greece. Both fossil trees resulted in overview models of good quality from which details of the bark and roots at the substrate surface are visible. The third paleobotanical object is our so-called "Mystery Cone," a silicified *Araucaria* seed cone from northern Wyoming that could be digitized into a high resolution 3D model with exquisite detail; the detail is so fine that the individual seeds within the abraded cone scales can be observed. The 3D model of the fossil cone is thus a source of gross morphology and fine-detail surface data. The further use of the paleobotanical models is manifold: Apart from the scientific application, the 3D models could serve as archival information or could be turned into 3D printings for museum exhibitions or teaching. It is hoped that the illustration of these examples will catalyze the use of photogrammetry in the study of fossil plants in the near-future.

Poster

## Exceptional preservation, preparation, and documentation: Pinus timleri seed cones from the Rhenish brown coal as an example of the scientific potential of a new collection at the Steinmann Institute

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Detailed locality and stratigraphic information combined with durable preparation are requisite for scientific work on palaeontological reference collections. The privately assembled Palaeontological Collection Rolf and Anne Gossmann holds promise for scientific application containing about 20,000 specimens featuring up-to-date provenance data from recently understudied fossillagerstätten. Main foci, among others, are plant fossils from the Rhineland of Lower Devonian to Quaternary age such as the Lower Devonian flora of the Rhenish Massif, the Middle Devonian flora of the Bergisches Land (including the earliest trees), the Upper Carboniferous flora of the Aachen coal, the Cenozoic fossillagerstätten of the Siebengebirge, and the Quarternary of the eastern Eifel. The collection is currently being dedicated to the Steinmann Institute of the University of Bonn. Digital specimen catalogues containing detailed machine-readable stratigraphic and locality information will be made available online by next year but can be currently accessed for study. As an example, here we describe the external morphology of exceptionally preserved cones and cone fragments of the largest taxon of Neogene seed cones from the Lower Rhenish Basin (Germany), *Pinus timleri*. Seed cones and fruits from the Rhenish brown coal in the Gossmann Collection have mostly been impregnated with polyethylene glycol 4000 for high durability and ease of study of the fragile specimens. *P. timleri* seed cones are asymmetric with a smooth side and erect umbos on the apophyses of the other side. We hypothesise that the smooth side grew shadow-exposed, while the side with more erect umbos was facing towards the direction of most intense light, as seen in extant morphologically similar *Pinus* species. As a possible mechanism for this pattern we propose higher rates of seed predation by insects on the regularly warmer sun-facing side of the cone.

Funding was provided by Landschaftsverband Rheinland (LVR) and the University of Bonn.

Poster

## An evolutionary pattern of plant-insect interactions on Persian ironwood, *Parrotia persica*, over the last three 3 million years (Pliocene and Pleistocene) in the Hyrcanian mixed forests, Iran

**Mahdieh Malekhosseini**[1], **Jest Rust**[1], **Torsten Wappler**[1,2]

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Plant-insect interactions is a fundamental ecosystem process that affects trophic levels and plant abundance and plays a major role in understanding climate changes in terrestrial ecosystems. Up to now, most fossil material is used to understand climate changes in deep time, but there is only poor knowledge concerning modern forests. The Hyrcanian forest in Iran contains relict genera and is a modern analog of paleoforests from the Cenozoic period, like, Bernasso (Pleistocene, France) and Willershausen (Pliocene, Germany). The aim of our study is to clarify effects on multitrophic interaction that could have been affected by environmental changes. A total of 2160 fallen leaves were collected from five transects: Astara, Rahim Abad, Molla Kala, Pasand, and Aliabad-e-katul along the northern coast of the Caspian Sea between montane (1000 m a.s.l.) and lowland (25 m a.s.l.) communities in the Hyrcanian forest. Leaf damage produced by insects has been studied, and leaf mass per area (LMA) was calculated. The rarefaction was calculated using R software. We used ANOVA to check if there are any significant differences between the FFGs and Removed area on each transect. In summary, 84% of the leaves were damaged, and we recognized six functional feeding groups (FFGs) and 32 damage types (DTs). Results showed that damage metrics on *Parrotia persica* can be correlated with LMA, temperature, and precipitation from west to east. On the western site (Astara), the highest rate of the (DTs) was recorded (96%), while it decreased to 71% in Aliabad-e-katol with increasing LMA. In conclusion, this study allows us to show low diversity and occurrence of damage diversity in comparison to fossil records which clarifies enhanced resistance in *P. persica* against herbivores in modern forests and could be considered as a key factor in the evolutionary arms race in paleoecology.

**Talk**

## Modern and Ancient Thieves: Krameria lappacea, a Hemiparasitic Shrub with Distinctive Wood as a Modern Analog for Fossil Hemiparasites

**Samantha Moody**[1], **Carole T. Gee**[1], **Maximilian Weigend**[2]

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Living plants are used as modern analogs for fossil species in climate and habitat reconstructions. *Krameria lappacea*, commonly known as the Peruvian rhatany, is a long-lived, woody hemiparasite in the cold deserts of the Andes. In the fossil record, it is possible that there are species that are hemiparasitic that have gone undiagnosed as such. Here we identify criteria through the study of the wood anatomy of a known hemiparasite and reliable climate data that could lead to the recognition of hemiparasitic woody plants in the fossil record. In the thin-sectioned wood of eight individual *K. lappacea* shrubs, cell dimensions and densities were measured, and standard wood indices were calculated. Comparisons of growth ring widths with mean annual temperature and precipitation for 25 years (1985–2010) showed no significant correlation, meaning the steady rates of growth observed in the growth rings of *K. lappacea* are not due directly to climate. It can be inferred that its growth is influenced by their parasitization of neighboring species for water and mineral nutrients. Like most desert plants, the wood of *K. lappacea* possesses numerous vessels per unit area, narrow vessels, shorter vessel element lengths, and has vasicentric or vascular tracheids, which are distinctive features of xeromorphy. However, the wood of *K. lappacea* differs in lacking other characteristic dry-climate traits such as helical thickenings and grouped vessels, which may be attributed to its hemiparasitic lifestyle. There are other modern hemiparasitic species that have wood anatomies like that of *K. lappacea*. This unusual suite of characters could be potentially used to identify a hemiparasitic woody plant in well-preserved fossil wood in the fossil record and thus infer the habitat and climate in which it lived.

**Talk**

## Combining insect herbivory and leaf trait data – A case study from the late Eocene of central Germany – preliminary results

**Christian Müller**, **Lutz Kunzmann**

*Senckenberg Natural History Collections Dresden, Germany*

The study combines insect herbivory and leaf trait data of two late Eocene leaf assemblages from the central German Leipzig Embayment with the aim to estimate the impact of habitat differences on plants and related interactions with insect herbivores. Assemblage 1 comes from the opencast mine Profen-Süd and was collected from the underbedding horizon of the main lignite seam complex (Zeitz Member, Borna Formation). This horizon is called Luckenau Clay and represents sediments of a coastal alluvial braidplain. The macroflora of the gravel pit Klausa, assemblage 2, was collected from abandoned channel fill deposits (silts and clays) within the fluvial sequences of the “Zwickau-Altenburger” river system (Borna Formation); deposited in the southern margin of the Leipzig Embayment. Thus the assemblage belongs to an adjacent but distinct palaeohabitat in the fluvial hinterland.

Both assemblages indicate the presence of the characteristic late Eocene *Steinhauera subglobosa- Rhodomyrtophyllum* riparianforest of the Zeitz floristic complex (middle to late Eocene). The macroflora of Profen-Süd differs from Klausa by the absence of complex character elements such as the conifers *Doliostrobus taxiformis* and *Quasisequoia couttsiae, Eotrigonobalanus furcinervis* (evergreen tree; Fagaceae), *Polyspora saxonica* (evergreen shrub or small tree; Theaceae)or *Toddalia hofmannii* (evergreen woody climber; Rutaceae). Nevertheless, the Profen assemblage is characterized by a markedly diversity of 30 dicot morphotypes, previously unknown from the Leipzig Embayment.

Insect herbivory data indicate, unexpectedly, a decrease in insect damage type diversity based on 400 leaves (indicator for insect diversity) between Klausa (10.92 ± 1.10) and Profen (14.78 ± 2.12). This trend is also visible when specialized damage types (Klausa: 1.97 ± 0.16, Profen: 4.31 ± 1.37) and galling damage types (Klausa: 0.97 ± 0.16, Profen: 2.86 ± 0.84) are selected. Damage type diversity, especially for galling, should increase from the braidplain to the hinterland based on the assumption of more stable habitat conditions (e.g. reduced humidity stress through flooding). The frequency of leaf damage, an indicator for insect abundance or consumption, increased remarkable between the two localities (Klausa: 11.71 ± 1.34%, Profen: 6.1 ± 0.6%), especially of the generalist external foliage feeding group margin feeding (Klausa: 8.22 ± 1.15%, Profen: 1.4 ± 0.29%).

Functional leaf trait data include the morphological (leaf shape, leaf margin, leaf venation) and morphometrical (leaf area, leaf mass per area) parameters, moreover, the Trait Combination Type analysis for the gross-morphological classification of the fossil leaves was applied to the assemblages.

Poster

## From animal to plant kingdom: Siphonia bovista Geinitz, an alleged sponge from the Cretaceous of Saxony (Germany), in fact represents inner moulds of the cone-like plant fossil Dammarites albens Presl in Sternberg, 1838

**Birgit Niebuhr**

*Senckenberg Naturhistorische Sammlungen Dresden, Germany*

The smooth *Siphonia bovista* Gein., introduced as a siliceous sponge by Hanns Bruno Geinitz in 1871, is interpreted as inner sandstone mould of the cone-like plant fossil *Dammarites albens* Presl in Sternberg, 1838, representing the outer sandstone mould of the same organism, just in different preservation. Apart from the globular to egg-shape outline, the size ratios and similar lateral flattening due to compaction, the conspicuous inward-arching of the basal area around the maximal 10 mm short stalk is characteristic for both fossils. Cone-like plant bodies and the corresponding up to 150 mm long lanceolate leaves of the salt-tolerant dwarf gymnosperm *D. albens* are always found in the lowermost marine sandstones of the Bohemian and Intrasudetic Cretaceous basins (Middle–Upper Cenomanian), overlying fluvial to brackish sediments. The same is true for *S. bovista* of the Saxonian Cretaceous Basin: all specimens were found in the lower Upper Cenomanian Unterquader of the Oberhäslich Formation, overlying the uppermost brackish Wurmsandstein of the otherwise fluvial Niederschöna Formation. Thus, environment and sedimentary conditions as well as stratigraphic position of *Siphonia bovista* Gein. and the cone-like plant bodies and leaves of *Dammarites albens* Presl in Sternberg of Germany, the Czech Republic and Poland are identical. The species name *Siphonia bovista* Geinitz, 1871, introduced for a siliceous sponge, is a rejected name and, therefore, replaced by *Dammarites albens* Presl in Sternberg, 1938. The reinterpretation of *Siphonia bovista* Gein. from Saxony provides the first proof of *Dammarites albens* Presl in Sternberg for Germany. The minimum stratigraphic and palaeogeographic range of the endemic gymnosperm is (Middle) Cenomanian up to the Turonian/Coniacian boundary interval of Europe (Poland, Czech Republic, eastern Romania, Austria, and Saxony in eastern Germany) between the 32° and 40° northern palaeo-latitudes.

Talk

## Medullosen – vielfältig, gut angepasst und dennoch ausgestorben?

**Ronny Rößler**

*Museum für Naturkunde, Germany*

Aktuelle Grabungsfunde werfen neues Licht auf eine der interessantesten aber auch rätselhaftesten Pflanzengruppen der Erdgeschichte – die Medullosen. An der Typuslokalität Chemnitz (frühes Perm, 291±2 Ma, Chemnitz Becken, Leukersdorf-Formation) stellten sie nicht nur unerwartet den größten Teil einer dichten hygrophilen Pflanzengesellschaft. Aufgrund ihrer besonderen physiologischen Eigenschaften, vor allem des enormen Wasserleitvermögens, trugen sie entscheidend dazu bei, anderen Pflanzen der heterogenen und zumeist juvenilen Vegetation einen geeigneten Lebensraum zu schaffen. In einem unreifen alluvialen Paläoboden wurzelnd und streng saisonalen klimatischen Bedingungen ausgesetzt entwickelten sie spezialisierte Wasserspeicher- und versorgungssysteme. Diese suggerieren mehrfach den Vergleich mit rezenten Cycadeen, für die Wurzeln aufgrund einer Ähnlichkeit mit den coralloiden, symbiotisch aktiven Wurzeln letzterer, für die Stämme aufgrund eines hohlzylindrischen, mehrschichtig-horizontalen Tracheidennetzes, vergleichbar den Gürtel-Blattspuren der Cycadeen.

Die Fossillagerstätte Chemnitz bietet im internationalen Vergleich eine bemerkenswerte Vielfalt an Medullosen und dies gleichermaßen für ihre mutmaßliche Artenzahl als auch ihre Wuchsformen. Weitere nachgewiesene Organzusammenhänge ebnen den Weg zu seit Jahrhunderten erhofften Komplettrekonstruktionen. Die markreichen, holzarmen Stämme vom Typ *Medullosa leuckartii* waren armiert von den Wedelstielbasen – spiralig dicht angeordnet, sklerenchymatisch, persistierend. Bekannt unter dem Taxon *Myeloxylon elegans* zeigen diese mehrfach taphonomische Nähe zur Beblätterung *Taeniopteris abnormis*.

Eine Stammkrone von *Medullosa stellata,* die unter der Last feuchter Pyroklastite regelrecht abgedreht wurde, zeigt mehrere Kränze noch ansitzender Wedel vom Typ *Alethopteris schneideri.* Erste Einblicke in die seit 5 Jahren laufende Präparation dieses Fundes machen die Herausforderung paläobotanischer Forschung anschaulich. Die Leitbündelarchitektur des terminalen Stammes konnte an diesem Exemplar zum ersten Mal im Detail untersucht werden. Dabei wirft die auffällige Konstanz der regelmäßig verzweigenden Bündel nicht nur neue Fragen zur ontogenetischen Entwicklung dieser stattlichsten Farnsamer-Bäume auf, sondern auch zur Systematik der Medullosen, die bislang auf einem weltweit sehr fragmentarischen Fossilbericht fußt. Leider bringen die anatomisch am vollständigsten erhaltenen Exemplare im Mikro-CT nur bedingt Resultate, während Tufferhaltungen mit nur partieller Silifizierung ganz neue Einsichten gewähren. Die mächtigsten Holzstämme der Medullosen weisen rhythmische Wuchsunterbrechungen auf, die im Lebensraum gut mit den Zuwachszonen der Cordaiten und Koniferen korrelieren.

Ganz im Gegensatz zu sämtlichen anderen Vegetationselementen im Perm von Chemnitz gibt es auch nach über 250 Jahren Sammeln und Forschen keinen Hinweis auf Fraßspuren an Medullosen – eine weitere Parallelität zu den mit hocheffizienten Neurotoxinen ausgestatteten Cycadeen? Trotz der neuen Erkenntnisse zur Anatomie, Physiologie und Paläoökologie dieser eigenartigen Samenpflanzen mit Farnwedeln wird noch ein weiter Weg zu beschreiten sein, um die Anzahl natürlicher Arten im Habitat bestimmen und von ontogenetischen Stadien und Erhaltungsformen sicher unterscheiden zu können.

Talk

## Taxonomy and taphonomy of a remarkable lycopsid mass-assemblage from the Morro do Papaleo outcrop (Rio Bonito Formation, lower Permian, Paraná Basin, Rio Grande do Sul, Brazil)

**Rafael Spiekermann[1], José Rafael Wanderley Benício[1], André Jasper[1], Dieter Uhl[2]**

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In Brazil, arborescent and sub-arborescent lycopsids are considered as important floristic components of the early Permian peat-forming vegetation of the Paraná Basin and have generally been assigned to *Brasilodendron pedroanum* Chaloner et al. 1979. However, fossil genera such as *Lycopodiophloios* and *Cyclodendron* have also been described from the lower Permian deposits of the Paraná Basin. These plants are mostly preserved as impressions and compressions, which are very fragmented, incompletely preserved and lack reproductive structure. Consequently, the taxonomy and systematic position as well as the biology and ecology of the early Permian arborescent and sub-arborescent lycopsids from Brazil are still poorly understood.

During recent fieldwork a remarkable mass assemblage of *Brasilodendron pedroanum* axes has been discovered. These axes are preserved in the plant bearing sub-level N8b of the Morro do Papaléo outcrop, Rio Bonito Formation, early Permian of the Paraná Basin, Rio Grande do Sul state, Brazil. They are massively concentrated, without any preferential depositional orientation, forming a monotypical assemblage. They are unbranched and preserved as impressions. Three morphological patterns, occurring on distinct axes, were described for leaf cushions. This mass-assemblage is probably a result of allochthonous deposition and hydraulic size-sorting, within an 80 cm thick, fluvially (re-)deposited ash layer/tuffite. The massive concentration of *Brasilodendron pedroanum* suggests that this fossil taxon was an important floristic element somewhere in the upstream area of the braided river system preserved in the Morro do Papaléo outcrop.

Talk

## Deciphering silicification pathways of fossil forests: Case studies from the late Paleozoic of Central Europe characterised by cathodoluminescence microscopy

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Cellular three-dimensionally preserved plants belong to the most fascinating or most complete remains of the flora and their evolution during the Earth's history. Accordingly, the demand to decipher the secrets of petrifaction has been developed over centuries and has caused manifold attempts and curious experiments. Several questions and phenomena remained so far inexplicable, although there is some progress to understand single aspects of petrifaction. Cathodoluminescence (CL) microscopy has proved to be a promising approach in silicified wood research, because this method seems to reveal the formation history of different quartz generations due to detecting their lattice defects. We characterise silicified wood from five petrified-forest sites of the late Paleozoic of Central Europe, which illustrate common settings of petrified wood origination. Samples are described with respect to plant anatomical features, silica phases promoting petrifaction and host rock petrology both on macro- and microscale. CL patterns and spectra of the corresponding silica are presented and put into the taphonomic context. Results point to wood silicification as being a monophase or multiphase process. CL spectra of silicified wood are limited to the blue (390 and 440 nm), yellow (580 nm), and red (650 nm) emission bands, which may appear in different combinations and varying intensity ratios. Yellow CL is typical for initial silicification, reflecting quick precipitation under oxygen-deficient conditions caused by initial decay of the organic material. Blue CL is predominantly of secondary origin, resulting from replacement of precursor phases by a secondary hydrothermal quartz generation, or subsequent silicification of wood. The red CL emission at 650 nm can be related to a lattice defect (non-bridging oxygen hole centre – NBOHC). Additionally, the selected localities indicate CL patterns being useful for discriminating silicifications in volcanogenic deposits from those promoted in siliciclastic sediments.

In conclusion, CL yields the potential to reveal occurrence-specific characteristics in silicified woods, and thus may act as taphonomic fingerprint. Consequently, CL could break new ground in petrified wood analysis, e.g. provenance studies of anatomically preserved plants found as reworked clasts in fluvial or glacial deposits. But the need for further research on petrified wood CL not only refers to comparative studies of several localities from different depositional environments, but also demands for more detailed investigations of each single occurrence. *In-situ* preserved $T^0$-assemblages, for instance, like the early Permian Chemnitz Petrified Forest, are known to deliver different preservational forms occurring in different host rocks.

**Talk**

## Mesofossil analysis as a window into a Triassic coal-forest ecosystem of Gondwana

**Jan Unverfärth[1], Stephen McLoughlin[2], Benjamin Bomfleur[1]**

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We present preliminary results of an ongoing PhD study about well-preserved plant remains from the Triassic Leigh Creek Coal Measures (Carnian–Norian) of the Telford Basin (South Australia). Recently ceased open-pit mining operations have created extensive exposures of fossiliferous deposits, which enabled documentation and collection of exceptionally well preserved plant-fossil assemblages from 14 stratigraphic levels. Most remarkable are intercalations of paper coals that are composed of mass accumulations of mummified seed-fern fronds. The host deposits are unconsolidated to weakly lithified mudrocks of very low coal rank (lignite A to sub-bituminous C), which allows us to apply novel protocols for bulk maceration in order to retrieve large volumes of macro- and mesofossils via various treatments, e.g., using a combination of heated hexametaphosphate solution and Schulze's reagent. The so obtained bulk of organic macro- and mesofossils consists of a broad array of various plant parts and animal remains. The vast majority are leaves and leaf fragments with pristinely preserved cuticles, most of which belong to the Triassic seed-fern *Dicroidium* (Corystospermales/Umkomasiales). Other cuticle remains include the affiliated fertile organs (*Pteruchus* pollen organs and ?*Fanerotheca* cupules) together with fragments of net-veined *Rochipteris* leaves (Petriellales) and possible scale leaves of cryptogams. In addition, bulk-sample residues contain probable lycophyte megaspores, clitellate cocoons, and varying amounts of charcoalified mesofossils, including wood fragments and at least two types of fern foliage. Of further importance is the abundant evidence of biotic interactions, including various types of feeding damage, leaf mining, sap sucking, and possible galling. Future studies of this exceptional material will: (1) enable precise taxonomic treatment of the various fossil assemblages; (2) allow detailed interpretation of the biology and autecology of the constituting plant taxa; and (3) facilitate analysis of the rich record of plant-insect interactions in a Late Triassic Gondwanan coal-forest ecosystem.

# Topics 11: Fossilization and the quality of the fossil record

## 11a) The fossil record of evolution and evolutionary processes

Talk

### On the fossil record of chimaeroid (Holocephali) egg cases

**Jan Fischer**

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Holocephalan fishes of the order Chimaeriformes comprise the living families Callorinchidae (plownose chimaeras or elephantfish), Rhinochimaeridae (longnose chimaeras or spookfish), and Chimaeridae (shortnose chimaeras or ratfish) with 56 extant, mostly deep-water, species. They are exclusively oviparous (egg-laying) producing large, leatherly, bilaterally symmetrical protective cases composed of multilamellar collagen for their fertilized, yolky eggs. The up to 270 mm long cases are spindle-shaped, with a three-fold divison consisting of a bulbous, ovoid central trunk (body) tapering gradually at the anterior end into a truncate rostral section (beak) and at the posterior end into a long and slender caudal section (pedicle). The dorsal side of the case is convex, and the ventral side is concave. Altogether, the overall shape of the case perfectly corresponds with the spindle shape of the accomodated embryo. The lateral edges of the case are accompanied by a wing-like, ribbed, lateral web (flange) that tapers toward each end of the case. Differences in shape and ratios of the case parts, the width of the web, as well as the number and shape of the ribs are diagnostic for each family.

Fossil chimaeroid egg cases have been known for 150 years, but have never been a source of controversy as fossil elasmobranch (*Palaeoxyris, Fayolia*) egg cases have, due to their unequivocal similarity to extant specimens. So far, at least 47 specimens representing 11 distinguishable species and eight further records not yet classified at the species level have been described from Late Triassic to Oligocene, shallow to moderately deep, marine strata of Eurasia, North America and New Zealand. These remains are 100–400 mm in total length. They have been referred to the parataxonomic ichnogenus *Chimaerotheca*. Although all specimens are clearly assignable to extant callorhinchid and rhinochimaerid egg case types, distinct corresponding chimaeroid producers of the various fossil species are unknown because they are isolated finds. A holocephalan affinity for enigmatic saw- and butterfly-like remains, already described at the species level, has been justifiably questioned. Altogether, *Chimaerotheca* is in need of revision.

In the light of recent phylogenetic analyses the Carboniferous egg case types *Vetacapsula* and *Crookallia* show distinct holocephalian affinity too. Moreover, a callorhinchid case-like fossil from the Late Devonian of South Africa that has been referred to placoderms, brings into question a phylogenetic relationship of holocephalans to this group. Altogether, the oviposition strategy was probably similar to that of extant chimaeroids.

Talk

### Divergence time estimation in Cervidae: comparing node- and tip-dating approaches

**Nicola S. Heckeberg**[1,2], **Faysal Bibi**[2]

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Cervids are a diverse family of ruminants with a rich fossil record dating back to the early Miocene (~ 20 Ma). They are also well sampled for molecular and morphological data and therefore make a suitable group for divergence time estimation and total evidence phylogenetic approaches.

We investigated cervid phylogeny using nuclear and mitochondrial data from over 40 extant species and a morphological dataset that included 29 fossil species. Both node and tip-dating approaches were used to time-calibrate the tree, experimenting simultaneously with different prior and parameter settings. We also investigated the phylogenetic position of some of the oldest described cervids.

Separate analyses of nuclear and mitochondrial markers using 6 node calibrations gave similar divergence age estimates, with the origin of crown Cervidae at 19-17.5 Ma (mitochondrial) and 19.5-16.6 Ma (nuclear). Tip dating analyses with fossils resulted in an older divergence of Cervidae at 21.7-19.7 Ma, but predominantly younger age estimates otherwise, with the divergences of extant subfamilies all younger than 6.8 Ma.

These differences are not necessarily contradictory, but demonstrate the different approaches of divergence time estimation. Tip dating takes the age of each fossil into account simultaneously with phylogenetic placement and it seems more recent clades are dated younger and are more in line with the fossil record than with node-dating, in which the fossils are not included in the analysis. Both approaches are useful and complement each other resulting in a more detailed insight into the evolutionary history of cervids.

Poster

## The Triassic inland lake basin of Madygen (Kyrgyzstan, Central Asia)

**Jan Fischer[1], Ilja Kogan[2], Sebastian Voigt[1], Michael Buchwitz[3], Jörg W. Schneider[2], Philippe Moisan[4], Frederik Spindler[5], Andreas Brosig[6], Marvin Preusse[7], Frank Scholze[2], Ulf Linnemann[7]**

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The Madygen Formation is a 560 m-thick succession of complexly interbedded lacustrine, fluvial, and alluvial deposits outcropping near the village of Madygen in southwest Kyrgyzstan, Central Asia. Biostratigraphic and radioisotopic data point to a mid-Triassic (late Ladinian to early Carnian; 237 ± 2 Ma) age of deposition. Due to the abundance and the exceptional preservation of aquatic and terrestrial biota within floodplain and shallow lacustrine siltstones, the Madygen Formation has to be considered a conservation and concentration lagerstätte for fossil plants, invertebrates and vertebrates. The fine-grained sediments even preserved coloration pattern and surface reliefs in insects as well as skin impressions in some reptile fossils. Once situated in the transitional zone of the Euramerian, Siberian, and Cathaysian faunal and floral provinces, the Madygen lagerstätte offers a unique taphonomic window in the Early Mesozoic fossil record of nonmarine ecosystems. The Madygen paleoecosystem existed in a warm-temperate climatic zone with year-round rainfall in an area of low mountains at mid-northern paleolatitude, several hundred kilometers away from the nearest marine shoreline.

The diverse fossil record corroborates favorable living conditions. Distinct sedimentary subfacies and biotic associations can be reconstructed. The most conspicuous part of the Madygen ecosystem was formed by a large perennial lake supporting a biocoenosis with at least five trophic levels of water plants, aquatic invertebrates, bony fishes, freshwater sharks, amphibians, and a reptiliomorph. Oxygen and strontium isotope data of fish tooth enameloid indicate unequivocal freshwater conditions. The relative abundance of shark egg capsules and juvenile bony fishes show that the vegetated shorelines of the lake were a preferred area for reproduction, feeding, and provided shelter for juveniles of various fish groups. Common occurrence and abundance of trace fossils prove that the lake bottom was oxygenated. Surrounding the lake, a densely vegetated floodplain sustained a highly diverse entomofauna, which in turn was preyed upon by small- to middle-sized tree- and ground-dwelling tetrapods including synapsids and diapsids.

Apart from its role as the only better-known locality of continental Triassic biota in Central Asia, the high diversity and exceptional preservation of land plants (one of the most diverse Mesozoic floras of Eurasia) and insects (more than 25,000 insects of almost all contemporaneous groups have been found) qualify Madygen as a crucial study site for the evolution and ecological differentiation of these groups in Mesozoic terrestrial ecosystems in the aftermath of the P/T extinction event.

Talk

## A new glimpse into the early diversification of peracarid crustaceans – An exceptionally preserved pygocephalomorph from the Upper Carboniferous of Germany

**Paula G. Pazinato[1], Carolin Haug[1], Angelika Leipner[2], Joachim T. Haug[1]**

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Peracarida is a species-rich and diverse group of malacostracan crustaceans ("higher" crustaceans) that is characterized by a specialization of the females. Peracarid females possess a brood pouch ('marsupium') in which the eggs are deposited and early development takes place. Therefore, peracarids provide extensive broodcare, but (mostly) lack planktic larvae. Peracarida diversified in the Carboniferous with numerous groups being present such as Isopoda (woodlice), Amphipoda (side swimmers) or Tanaidacea. Another early branch within Peracarida is Pygocephalomorpha, a now extinct group most likely closely related to mysidaceans (opossum shrimps). Although some possible representatives have been interpreted as decapods, the presence of distinct brood pouches in several specimens supports an ingroup position within Peracarida.

The fossil record of pygocephalomorph crustaceans is quite abundant in supposedly brackish deposits from the Lower to Upper Carboniferous of Great Britain and North America, as well as in brackish deposits from the Lower Permian of Gondwana.

We present the first record of Pygocephalomorpha from the Upper Carboniferous of Germany. The single fossil specimen comes from the Piesberg Quarry, near Osnabrück. The fossil (preserved as part and counterpart in ventral view) is almost complete, including functional head and anterior trunk (thorax; unclear how many thoracic segments might be conjoined to the head) and posterior trunk (pleon). The fossil is covered with a thin layer of yellowish gumbelite, well contrasting against the dark claystone matrix.

The specimen provides access to the detailed morphology of many of the appendages and other ventral details to a remarkable degree. This includes: 1) Antennula with a peduncle (three elements) and two flagella. 2) Antenna with coxa, basipod, endopod (with flagellum) and a large, leaf-shaped exopod with inner margin lined with numerous setae. 3) Ventral region with eight (thoracic) sternites, trapezoidal in shape, and of similar length, but increasing in width. 4) The posterior six thoracic appendages with endopod and exopod arising from the basipod. The endopod is composed of five elements bearing numerous small setae, most densely on the most distal element. The exopod has a proximal region and a distal multi-annulated region, bearing plumose setae.

The caridoid appearance, along with the lack of proper preservation of thoracic appendages in many pygocephalomorphs led to the assumption by some authors that some crustaceans of this group are actually early decapods. The presence of exopods on the thoracic appendages of this fossil supports that pygocephalomorphs are not decapods, but part of the early diversification of Peracarida.

Talk

## A comparison of Givetian gastropod faunas from the Tata region (Dra Valley, southern Morocco) and the Rhenish massif

**Maro-Pascal Ellerkamp, Ralph Thomas Becker**

*Westfälische Wilhelms-Universität Münster, Germany*

Middle Devonian (Givetian) gastropods are widespread in the Rhenish Massif. The richest and most diverse assemblages occur in reef complexes, from biostromes to lagoons and marginal slopes of bioherms. The most famous localities are Sötenich (Eifel), Bergisch-Gladbach, Hofermühle, Schwelm, Hohenlimburg, and the Frettertal (Attendorn Reef). There are only a few faunas from deeper, subphotic volcanic seamounts, such as the Martenberg near Adorf. From the Rhenish Massif alone, ca. 330 species and 110 genera have been described. As part of a master thesis, unpublished Rhenish material of the Geomuseum Münster (WWU) and collections from the western Dra Valley of southern Morocco were examined. Together with the extensive literature data, they form the base for taxonomic and biogeographic comparisons. The Moroccan material is from three adjacent localities (Tiguisselt, Oufrane, and Oued Mzerreb) of the Tata region and was collected by RTB and Z.S. Aboussalam in 2000-2006. Locality data and the regional biostratigraphy were published by Aboussalam & Becker (2004), Aboussalam et al. (2004), and Becker et al. (2004). The three faunal successions are of great importance, because there is so far only very poor information on Givetian gastropods from all of NW Gondwana. Dra Valley gastropods are preserved as goethitic moulds and co-occur with abundant middle Givetian goniatites of the *Maenioceras terebratum* Zone (Middle Devonian II-C) to basal *Pharciceras* Stufe (MD III-A/B). Therefore, they enable a comparison between contemporaneous assemblages from neritic/reefal (Rhenish Massif) and hypoxic, pelagic facies (Dra Valley). The preservation of the Moroccan collection partly hampers a precise identification, which has to adopt a population approach, using specimens with impressed ornament as key representatives. Sometimes, shell parts were transformed to goethite. Preliminary data show that the Tata region assemblages consist both of new forms and of specific Rhenish neritic taxa, which had a much wider habitat range than previously known.

### References

Aboussalam, Z. S. & Becker, R. T. (2004): Givetian stratigraphy and faunas at Tiguisselt (Tata region, Dra Valley, Morocco). – Documents de l'Institut Scientifique, Rabat, **19**: 60-63.

Aboussalam, Z. S., Becker, R. T., Bockwinkel, J. & Ebbighausen, V. (2004): Givetian biostratigraphy and facies development at Oufrane (Tata region, eastern Dra Valley, Morocco). –Documents de l'Institut Scientifique, Rabat, **19**: 53-59.

Becker, R. T., Aboussalam, Z. S., Bockwinkel, J., Ebbighausen, V., El Hassani, A. & Nübel, H. (2004). The Givetian and Frasnian at Oued Mzerreb (Tata region, eastern Dra Valley). –Documents de l'Institut Scientifique, Rabat, **19**: 29-43.

Poster

## How similar is similar – mayfly larval morphology appears 'old', but is it?

**Gideon Haug, Carolin Haug, Joachim Haug**

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Mayflies (Ephemeroptera) are flying insects, easily identifiable by (usually) three thread-like structures arsing from their terminal ends. Within Pterygota, the group of flying insects, modern ephemeropterans are representatives of an old lineage, with their most likely sister lineage leading to Odonatoptera (dragonflies, damselflies and their fossil relatives, such as the super-sized griffinflies). Adult mayflies usually have four wings (although the hind wings can be fairly reduced) which cannot be folded onto the trunk, and usually lack functional mouthparts. As their Latin names suggest, they are pretty short-lived as winged forms and die after few days or even hours. Hence, the major part of their lives, often about two to three years are spent as aquatic larvae (also called nymphs or naiads). Comparably to the adults, also the larvae can be easily recognised, by the presence of three thread-like posterior structures, but additionally by prominent gills arsing from up to seven abdominal segments. In modern river ecosystems mayfly larvae play an important role as herbivores and detritivores, few species as predators of other insects, and also as prey for various fish species, but especially as important bioturbators. Fossil mayflies seem to resemble modern ones already to a large degree, not only as adults, but also as larvae. Connecting larvae and adults of fossil species is often challenging, making biodiversity estimations of the past tricky, as most mayfly taxonomy bases on adults, while as stated above ecological impact lies on the larval stages. Here we compare morphological traits of mayfly larvae through time to evaluate possible changes in ecological role of the larvae. In other words, we address the question: how similar do fossil mayfly larvae indeed resemble their modern counterparts? Fossil mayfly larvae are known from down into the Permian. Especially beautiful examples are known from Mesozoic deposits, and they are especially abundant in Cretaceous faunas such as the one from the famous Crato formation. Despite the theoretically good data base differences in preservation makes a comparison of all these forms still a challenging enterprise. We present first attempts to this morphological approach and discuss possible ways to overcome outlined difficulties.

Talk

## Fossil aquatic insect larvae in Burmese amber with important implications on the ground pattern of Odonata (dragonflies and damselflies)

**Mario Schädel[1], Patrick Müller[3], Joachim T. Haug[1,2]**

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Dragonflies and damselflies (Odonata) are iconic flying insects. They are not only easily recognizable as adults, also their larvae can be recognized by many non-entomologists. The most impressive feature of these larvae is their raptorial apparatus formed by the last pair of mouthparts (labial mask). Dragon- and damselflies share this apomorphy, and even though there are special adaptions of the labial mask in some lineages, the structure itself remains recognizable in all known modern odonatan larvae. Dragon- and damselflies can be easily differentiated as adults, but also in their larval stages. Larvae of both groups are aquatic and, due to their size, need special structures for gas exchange in water: Dragonflies (Anisoptera) possess rectal gills inside the abdominal cavity; damselflies (Zygoptera) have three external gills suspected to be formed by an extension of the tergite of the 11$^{th}$ abdominal segment (median gill) and extensions of the coxopodites of the very same segment (lateral gills). The lateral gills are not corresponding to the cerci, which are present in both dragon- and damselflies, although not as prominent as in many other insects. These structures belong to the ground pattern of the group that combines all modern odonatans, but their origin is still enigmatic. We present ca. 100 million years old fossil odonatan larvae from Cretaceous Burmese amber. The fossils are easily identified as odonatan larvae by the presence of a prominent labial mask, yet they differ significantly in the morphology of the terminal part of the abdomen. This different morphology provides significant implications for understanding how the abdominal structures, especially in damselflies, evolved and furthermore also for the reconstruction of the ground pattern of Odonata and with this also for the basal split events within flying insects (Pterygota). The ground pattern reconstruction is basis of our knowledge about the still enigmatic evolution of early pterygotan insect lineages ("the Palaeoptera problem"). Morphological and molecular studies still suggest conflicting hypotheses on how mayflies (Ephemeroptera) and dragon- and damselflies relate to the remaining winged insects (Neoptera). Our finding sustainably influences the morphological information on which this ongoing debate is based.

Poster

## Borkewehr near Wocklum (northern Rhenish Massif, Germany), a possible future Devonian/Carboniferous boundary GSSP section

**Sven Hartenfels[1], Ralph Thomas Becker[2]**

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In 1935 the Devonian/Carboniferous boundary was the first defined chronostratigraphic level, using the entry of the goniatite *Gattendorfia subinvoluta* in the Oberrödinghausen railway-cut (Hönne Valley, Rhenish Massif). Subsequent studies (Alberti et al. 1974) proved that the stratotype contains a hiatus right at the boundary (base of Hangenberg Limestone). This resulted in more than 15 years of intensive search for a new D/C definition and stratotype. Eventually, the conodont *Siphonodella (Eosiphonodella) sulcata* was chosen as the Carboniferous index fossil. The new GSSP was placed in an oolithic succession at La Serre (Montagne Noire, Paproth et al. 1991). In the course of geochemical studies, Kaiser (2009) discovered that the index conodont occurs at La Serre already below the GSSP level, just above a facies break and conodont-free interval. Since there are no other criteria to correlate the GSSP level with precision, another revision became inevitable. During a workshop in Montpellier (September 2016), the International D/C Boundary Task Group voted to consider the entry of *Protognathodus kockeli* as future GSSP level. Therefore, the search for successions, which record in the post-glacial Upper Hangenberg Crisis Interval (Kaiser et al. 2015) the phylogenetic change from ancestral *Pr. collinsoni* to *Pr. kockeli* became crucial.

*Protognathodus collinsoni* is characterized by irregularly distributed nodes on the upper surface of its slightly asymmetrical cup. The transition to *Pr. kockeli* is more complex than previously thought. The emended *kockeli* diagnosis of Corradini et al. (2011: a row of coarse nodes parallel to the carina on one or both sides of the cup) contains also intermediates between *Pr. collinsoni* and *Pr. kockeli* sensu Bischoff (1957, original diagnosis: with one or two lines of coarse nodes on the inner and outer side of the platform). The holotype is a very advanced form with two rows on each side; its precise provenance in the Borkewehr type section is unknown. Investigations of several localities proved that "*kockeli* morphotypes" with a row of nodes on only one side may occur in the first limestone immediately above the conodont-free Hangenberg Shale/Sandstone. Therefore, their entry is not useful for a boundary definition.

Our survey of Rhenish sections showed that the Borkewehr exposes best a sufficiently thick and fossiliferous *kockeli* Zone. The phylogenetic change from intermediate forms, which could be separated taxonomically, to advanced *Pr. kockeli* is recognizable in three beds of the transgressive Stockum Limestone. Therefore, the section conforms to the criteria for a future Devonian/Carboniferous GSSP.

Talk

## Iterative evolution as the rule – not exception – in ammonoids and other cephalopods

**Ralph Thomas Becker**

*Westfälische Wilhelms-Universität Münster, Institut für Geologie und Paläontologie*

Ammonoid have been called by Seilacher (1989) the "*Drosophila* of Palaeontologists" because of their very rich fossil record, high disparity and palaeodiversity, and especially because their shell ontogeny reflects phylogenetic trends. They are among the best macrofossil groups to document and investigate evolutionary transformations and patterns, from evolutionary change in population successions, variability in contemporaneous assemblages along palaeoecological gradients (e.g. palaeobathymetry), to aspects of speciation, adaptation (evolutionary ecology), "evo-devo" (e.g. paedomorphy), and palaeodiversity fluctuations. In modern biology, the significance of non-parsimonous, iterative evolution (convergence, homoplasy) is increasingly acknowledged, for example by genetic analyses of Caribbean *Anolis* lizards or African fresh water fish. In terms of genetics, iterative evolution can be easily explained by repeated variations of gene expression (variable activity of enhancer sequences) in closely related taxa with a principally very similar genome.

A complex "mosaic evolution" of ammonoids, with numerous iterations, is long-known and contributed to the resistance of the majority of specialists when cladistics phylogenetic approaches became "fashion". A review of morphological innovations confirmed that it is difficult to find apomorphies that developed only once during the ca. 350 ma of ammonoid evolution. This pattern applies equally to their ancestors, the Bactritida, and to the Coleoidea, which originated from the latter independently in the Carboniferous. Given examples range from the endless repetition of similar conch shapes (e.g. oxyconic and carinate shells, reversing rates of whorl expansion), the parallel "invention" of convolute whorls in the oldest members, the innovation of deep ocular sinuses at the aperture, the secondary shift of siphuncle positions, the introduction of new suture elements (A-lobes, Carboniferous subdivided E-lobes, ceratitic and ammonitic sutures), and "embryonic revolutions" (iterative loss of embryonic shell accretion) to strong similarities between Devonian clymeniids and some Cretaceous nautilids. Recent discoveries showed that even the change from ecto- to endocochleate shells occurred several times in cephalopod evolution.

The ammonoid/cephalopod evidence suggests that "maximum parsimony", the search for the lowest level of homoplasy, is a very ambiguous principle to identify the "most likely tree" in phylogenetic analyses. Within clades, iterative evolution does not require "unlikely" major genetic changes, just small variations of gene expression. In groups with a rich fossil record, common and long "ghost ranges" can be used to identify unlikely trees. This suggests to revalidate classical concepts of "strato- or chronophyletic" phylogeny.

Talk

## Ammonoid beginnings

**Christian Klug**

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Among the invertebrates, ammonoids might represent one of the best understood examples of the origin and early evolution of a major clade. This is probably due to the fortunate combination of abundance, wide distribution and good knowledge of ontogenetic trajectories preserved in their conchs. The transition from bactritids to ammonoids is quite well documented by fossils (Klug et al. 2015). The main evolutionary changes in the early phylogeny of ammonoids concern the rather steady increase in coiling and in whorl expansion rate, which even comprised the initial chamber and the embryonic conch (De Baets et al. 2012). These modifications in conch morphology likely impacted the locomotory abilities of these cephalopods, which was recently verified using virtual models based on image stacks obtained by grinding tomography (Naglik et al. 2016). In turn, this affected both their intraspecific variation through ammonoid evolution (De Baets et al. 2013) and their ecology. Recent findings of ammonoid mouthparts in the latest Devonian showed that all major clades of Devonian ammonoids had jaws and thus, jaws are part of the ammonoid Bauplan (Klug et al. 2016). The morphological differentiation of jaws between these clades corresponds to the synchronous increase in ammonoid disparity. Although the jaw morphology evolved to some degree in dependence of conch morphology (whorl cross section limits jaw shape), the disparity in conch and jaw morphologies suggest a differentiation in feeding and other habits.

DE BAETS, K., KLUG, C., KORN, D. & LANDMAN, N. H. (2012): Early evolutionary trends in ammonoid embryonic development. – Evolution, 66 (6): 1788-1806. DOI: 10.1111/J.1558-5646.2011.01567.X

DE BAETS, K., KLUG, C. & MONNET, C. (2013): Intraspecific variability through ontogeny in early ammonoids. – Paleobiology 39 (1): 75-94. DOI: 10.1666/0094-8373-39.1.75

KLUG, C., FREY, L., KORN, D., JATTIOT, R. & RÜCKLIN, M. (2016): The oldest Gondwanan cephalopod mandibles (Hangenberg Black Shale, Late Devonian) and the Mid-Palaeozoic rise of jaws. – Palaeontology, 59 (5): 611-629. DOI: 10.1111/pala.12248

KLUG, C., KRÖGER, B., VINTHER, J., FUCHS, D. & DE BAETS, K. (2015): Ancestry, origin and early evolution of ammonoids. – In: KLUG, C., KORN, D., DE BAETS, K. KRUTA, I. & MAPES, R. H. (eds.): Ammonoid paleobiology, Volume II: from macroevolution to paleogeography. Topics in Geobiology, 44: 3-24, Springer, Dordrecht.

NAGLIK, C., RIKHTEGAR, F. N. & KLUG, C. (2016): Buoyancy in Palaeozoic ammonoids from empirical 3D-models and their place in a theoretical morphospace. – Lethaia, 49 (1): 3–12. DOI: 10.1111/let.12125

# 11b) Taphonomy: Inferences about ecosystems and paleobiology

**Poster**

## Identifying species, dealing with deformed specimens – thoughts on the species of the pygocephalomorph group Liocaris from the Lower Permian of Brazil

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Assessing diversity (in the sense of species richness) over time is a challenging task. It heavily depends on a reliable identification of possible species as such. Especially different aspects of preservation may lead to the impression of more species than actually present. We present a possible case for pygocephalomorph crustaceans.

The Irati Formation of Paraná Basin (Brazil) is a rock succession comprising layers of dark shales intercalated by dolomitic siltstones, representative of the epicontinental sea that was formed during the Late Carboniferous between South America and meridional Africa. The most characteristic fossils of this sequence are mesosaur reptiles and pygocephalomorph crustaceans. Traditionally, six genera and nine species of pygocephalomorph from the Irati Formation were differentiated, specimens of *Liocaris* being the only ones recorded in the dolomitic layers. The original description of *Liocaris* Beurlen, 1931 was based on isolated shields, distinguished into two types, in the author's view two species, *L. huenei and L. angusta*.

We present new features of specimens identified as *L. huenei.* These are silicified specimens, preserved non-flattened, three-dimensionally. Not only shield, also most parts of the body proper including posterior trunk (pleon) are preserved. As originally described, the margins and surface of the shield are smooth, with a small rostrum and a transverse cervical groove of about one third the length of the entire shield. Antennula (with two multi-annulated flagella), antenna (with flagellum and antennal scale) and large pedunculate eyes are preserved. Distal parts of the thoracic appendages are not preserved, yet female specimens preserved in ventral view exhibit seven pairs of overlapping oöstegites, forming the brood pouch (marsupium). The pleon exhibits six segments of similar length and width. The tail fan, composed of biramous uropods and telson, is folded ventrally.

According to Beurlen, the main difference between *L. huenei* and *L. angusta* is the ratio of width and height of the shield. In the first, it is 2:1, while in the latter it is 1:1. Yet, the original description did not consider that the isolated shields could represent moult remains (exuviae). When detached from the rest of the body, the shield seems to be able to change its original shape, folding its lateral margins ventrally; this appears to be the case in *L. angusta*. Once the shields are covered with matrix, the appearance is that these are almost circular in shape. Therefore, we propose that *L. angusta* is actually a taphonomic variation of *L. huenei*.

**Poster**

## The age structure of the Europasaurus assemblage from the Langenberg quarry (Kimmerdgian, Upper Jurassic, Lower Saxony, Germany)

**Michael Scheil[1], Oliver Wings[2], Nils Knötschke[3], Paul Martin Sander[1]**

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Sauropods were the dominant Mesozoic herbivores, and are interesting especially in terms of ecology and gregarious behavior such as herding. Commonly cited evidence for herding in dinosaurs are mass accumulations. Such an accumulation of bones, consisting both cranial and postcranial material, is found in Upper Jurassic shallow marine limestones exposed in the Langenberg quarry near Goslar (Lower Saxony, Germany). The bones are attributed to the dwarf sauropod taxon Europasaurus holgeri and represent two different-sized morphs. Here we test the hypothesis that this accumulation represents a former dinosaur herd, or at least a part of a herd. By using the "Minimum Number of Individuals" approach, it was possible to determine the number of individuals preserved in the accumulation of at least 21. A body size analysis based on frequency distributions of scapulae and femora shows that very small (young) and very large (old) individuals are underrepresented in the fossil material, as in a recent herd. Most of the assemblage records not fully grown animals, and the two morphs occur at roughly even frequency in the postcranial material. The Langenberg assemblage thus is the result of catastrophic mortality and suggests that Europasaurus lived in herds, possibly with an even representation of the sexes. A possible taphonomic scenario invokes a herd, or at least part of a herd, being killed by a catastrophic storm surge or a flood. The carcasses were washed into the sea and embedded in the marine sediments. Herding in Europasaurus invites further work on gregariousness of sauropods.

# 11c) Soft part preservation: The limits of the fossil record

Talk

## Soft-tissue preservation of resin-embedded arthropods

**H. Jonas Barthel, Jes Rust**

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Amber and copal occur in deposits of various ages around the world and resemble important sources of terrestrial fossil arthropods as they preserve inclusions in a three-dimensional way, often combined with an ultrastructural fidelity. Hypotheses regarding the exceptional conservation of inclusions in resinites range from fixation and rapid dehydration to inhibition of microbial activity. Based on naked-eye observation and several analytic approaches, it is indicated that the fossilization of amber is not a uniform process. The preservation quality widely varies between deposits and as a consequence, the taphonomic pathway and its main drivers remain poorly understood. We want to analyze which processes lead to the preservation of non-mineralized soft tissue in amber and copal samples from several deposits by applying a standardized method which includes breaking and dissolving of the resinite matrix combined with a subsequent chemical analysis. It is planned to compare our measurements to museum and extant samples as well. Here, our first results are presented on samples from Eocene Indian amber and Quaternary Madagascar copal, comprising SEM images, histologic slices, and Raman spectra.

Talk

## In vitro alteration of tooth enamel in isotope tracer solutions

**Katrin Böhm[1], Thomas Tütken[1], Regina Mertz-Kraus[1], Denis Fougerouse[3], Thorsten Geisler[2]**

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Stable isotope ratios and trace element concentrations of fossil bones and teeth are important geochemical proxies for the reconstruction of diet and past food webs in archaeology and palaeontology. However, diagenesis can significantly alter diet-related isotope signatures and elemental compositions. Here, we report the results of *in-vitro* alteration experiments of tooth enamel and dentin from a modern African elephant molar in aqueous solutions in cold-seal Teflon vessels at 30 °C and 90 °C. Cubes of dental tissue with ~3 mm edge length were put into 2 ml of an acidic aqueous solution enriched with different isotopes (D, $^{10}B$, $^{18}O$, $^{25}Mg$, $^{44}Ca$, $^{67}Zn$, and $^{86}Sr$) for up to 63 days. Additionally, also shark teeth were immersed in this solution to assess whether fluorapatite (enameloid) is characterised by a different resistance against alteration than hydroxylapatite (enamel). Element and isotope distribution profiles across the dental cubes and shark teeth were measured with LA-ICP-MS and electron microprobe prior to and after the experiments. Additionally, Raman spectroscopy and atom probe tomography (APT) were applied to characterise and quantify the alteration at the microscopic down to the atomic scale, respectively. The unbuffered experiments started at a solution pH ~1, but the pH increased within four days to values between ~6 and 7, and then remained at that level. Isotope ratios measured by LA-ICP-MS revealed an altered outer rim of ~100 µm in the enamel of all cubes already after four days at 30 °C. Whereas in the enamel no systematic further increase of alteration depth occurred over time, the dentin was fully altered after one week. After ~2 - 3 weeks, the tracer solution started to penetrate through the dentin into the enamel. The enameloid and dentin of the shark teeth are both fully altered after only 18 days at both temperatures, suggesting that fluorapatite is not necessarily more resistant against alteration than hydroxylapatite. The nanoscale analysis of altered and unaltered dentin at 90°C for 21 days by APT revealed a network of hydroxylapatatite crystals defining a porous structure. The pores are partly filled with C (and Mg), likely representing relic organic material. The distribution of the isotopic tracer in the altered sample further suggests that the hydroxylapatite nano-crystals were entirely replaced during the experiments. Diagenetic processes leading to alteration will be further discussed in more detail based on Raman spectroscopy data measured along enamel alteration gradients.

Talk

## Experimental data on constraining the „Fossilization Window“ - the effects of pressure, salinity and the pH-Eh-values of seawater

**Fabian Matthias Gäb[1], Chris Ballhaus[1], Joachim Mogdans[2]**

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The exact conditions under which fish are fossilized, are not very well known, despite being the subject of intensive research both in the field and in the laboratory. The basic premises are the isolation of the carcass from scavengers and the introduction of the carcass into a milieu where the decay of organic matter is slow and the replacement of organic matter through inorganic substances is fast. Possible conditions that would aid the preservation are: anoxic conditions in the water, fast burial by sediment, or preservation in hypersaline bottom layers of stratified basins, so saline that scavengers are kept away.

Within the DFG funded research group FOR 2685 we conduct experiments to simulate conditions suitable for fossilization using the Solnhofen Fossillagerstätte as a natural analogue. The Solnhofen basins are thought to have been stratified with respect to salinity and redox conditions, with hypersaline, reduced bottom layers overlain by oxidized seawater. As a first step, we have determined the pressure conditions under which dead fish would sink to the bottom. Dead fish is placed in a pressure vessel in water with variably salinity, and the pressure is increased until the fish starts to sink. We found that the needed pressure increase to prevent the fish from floating in fresh water is < 0.5 bar and rises up to > 8 bar at a salinity of 15 wt.% NaCl. Given that the pressure in a water column increases very rapidly when moving deeper, increasing the ambient pressure is a suitable way, to prevent a deceased fish from floating and to initiate sinking in a hypersaline bottom layer.

Presently, we are exploring the decay rate of fish under reduced conditions (Eh < -240 mV) as a function of water salinity. In normal seawater, the disarticulation of fish carcasses is too fast to form an intact fossil. In seawater brine evaporated to around 12 wt.% NaCl equivalent, no disarticulation is observed within about three weeks. Our preliminary conclusions are that the key to generate fossil lagerstätten like Solnhofen are hypersaline conditions, of dense bottom waters exceeding 12 wt.% NaCl under reduced conditions, with Eh close to lower stability limit of sulfate. Such waters are likely to be aragonite oversaturated. Until now, no aragonite was observed but future experiments will reveal how fast fish carcasses can be mantled by carbonate and preserved for the fossil record.

**Poster**

## U-Pb analyses of fossil bone apatite from the Upper Jurassic Morrison Formation (USA)

**Felix Graeber, Frank Tomaschek, Markus Lagos, Martin Sander, Thorsten Geisler**

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There is a high abundance of sauropod bones in the fossil record that are well preserved even at the microstructural level. The confirmed ages of these fossils are mostly chronostratigraphic ages, but incorporation of trace elements during the fossilization process makes bones apatite amenable to radiometric dating, too. However, due to the nano-crystalline and chemically reactive character of biominerals, they might be susceptible to changes in the burial environment which could cause an uptake or loss in trace elements. In this scenario, present chemical and isotopic compositions would not necessarily reflect early diagenetic conditions. Instead, they might provide a record of a long-term diagenetic evolution.

Bones from the Upper Jurassic Morrison Formation (USA) are perfectly suited to test this hypothesis. Postdating deposition, the south-western part of the Morrison Formation was affected by the Sevier-Laramide orogeny. Regional basin studies have identified sequences of authigenic minerals, as well as remobilized uranium ores (e.g., McLemore 2011). In this pilot study, we investigated the apatite U-Pb system of three sauropod bone samples from the Morrison Formation. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) makes rapid micro-analysis possible, and measurements can be linked to the texture of the investigated tissue. Covering a range of bone areas, distinguished by their optical properties, or by the presence of secondary mineral phases, such as diagenetic calcite and iron oxide precipitations, may help in identifying different age domains within one sample.

The measured U-Pb isotopic ratios for each sample scatter along single arrays in a Tera-Wasserburg diagram. Whereas a few analyses result in single spot ages which proxy the Jurassic deposition age (~ 150 Ma), the majority yields Cretaceous age populations of ~ 110 Ma and ~ 80 Ma, respectively. While some domains may have remained unaffected since early diagenesis, most parts of the bones have apparently been reset during a later overprint. A similar range of Cretaceous radiometric ages is known from remobilized ores of the Grants Uranium District, providing a link to the regional basin evolution. In conclusion, fossilized bone apatite may remain a closed U-Pb system over geologic time scales. However, fossil bone does react to events affecting the diagenetic conditions in depositional basins. The U-Pb system of bone apatite might allow for tracing these long-term diagenetic processes.

**Reference**

McLemore, V.T. (2011): The Grants Uranium District, New Mexico: Update on source, deposition, and exploration. The Mountain Geologist 48, 23-44.

**Poster**

## The impact of bacterial activity on decay and fossilization of arthropods: An experimental approach

**Kathrin Janssen[1], Ursula Steffens[1], Bastian Mähler[2], Jes Rust[2], Gabriele Bierbaum[1]**

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The fossilization process in aquatic environments is influenced by abiotic (temperature, oxygen condition, salinity, pH value, water- and sediment chemistry) and biotic factors. Especially the impact of bacterial activity remains an unexplored territory. In addition to the decay of organisms, it has been shown that bacteria also contribute to the formation of fossils by synthesizing biofilms. Such biofilms later fossilize by precipitation of minerals and yield casts or pseudomorphs of hard and soft tissues of the carcass. There is nothing known about the species that mediate the processes and if they are intrinsic (gut) or extrinsic (water) microorganisms. Preliminary experiments under controlled laboratory conditions gave insights into the microbial diversity and changes in the composition of bacterial community. To observe microbial shifts during decomposition, two experimental setups were investigated. Two crayfish specimens of *Cambarellus chapalanus* were determined at the beginning of the study. Both tested animals harboured an individual gut microbiome including symbionts. Another four dead specimens were placed each in one airtight vessel filled with tank water and stored at a constant temperature of 30 °C for 14 days. Oxygen saturation and pH values were measured constantly. For microbiome sequencing, the DNA from water and crayfish samples was extracted and sequenced. The resulted reads were aligned with each other. All reads with 97 % identity were sorted into 775 different OTUs (operational taxonomic units) which were then compared to a curated database of 16S rRNA sequences. 347 different species or genera could be detected in the samples. Only 56,8 % of the obtained organisms had been cultured before, the other 43,2 % had only been detected in metagenomics datasets so far. On day seven the microbiomes of two decaying crayfish were determined. The decayed samples showed a great similarity (323 and 365 OTUs, respectively, with 267 OTUs present in both samples (82 % or 73 %) and that the microorganisms derived mostly from the water. After 14 days the last two water- and crayfish-samples were investigated. They contained a high proportion of anaerobic species which demonstrated an adaptation of the microflora to the lack of oxygen at this time. The overall goal of this project is to improve the general understanding of decay and fossilization processes connected to the microbial activity. Besides the observation of physical disarticulation, influence of chemical, physical and biological parameters will be tested to identify the best conditions for mineralization and fossilization of arthropods.

Talk

## Experimental alteration of a carapace cuticle of Hemigrapsus takanoi (Decapoda: Varunidae)

**Bastian Mähler[1], Gabriele Kühl[1], Hans-Jürgen Ensikat[2], Natascha Kuhlmann[1], Jes Rust[1], Thorsten Geisler[1]**

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Arthropods represent the highest biodiversity among metazoan. Insights into evolution and phylogeny of arthropods are derived from exceptionally well-preserved fossils from so called conservation deposits (Konservatlagerstätten). These fossils were formed by a complex sequence of biological, chemical, and geological processes that starts immediately after death of the organism. To study the fossilization process of arthropods, we embedded an individual of *Hemigrapsus takanoi*, collected at the north-east coast of the island of Sylt (Germany), inside alluvial mudflat sediments and stored the sample at 24°C ± 1°C for about 1.5 years in a closed plastic box. At the end of the experiment, fragments of the altered carapace cuticle were recovered from the mud and embedded in epoxy resin, cut, polished, and then analysed by back scattered electron (BSE) imaging and element mapping with a scanning electron microscope equipped with an energy dispersive X-ray detector (SEM-EDX), and confocal hyperspectral Raman spectroscopy. The same procedure was performed with a fresh sample for comparison. BSE imaging showed complex alteration features of all three carapace cuticle layers in the altered specimen. In addition, a reaction front was noticed in the endocuticle, growing from internal to external surface of the carapace. SEM-EDX element mapping of the same specimen showed a higher concentration of Ca inside the reaction front than in the rest of the endocuticle layer. Analyses of the fresh specimen by Raman spectroscopy revealed typical chitin bands and a broad band near 1079 $cm^{-1}$, which is related to the fully symmetric $v_1(CO_3)$ stretching mode of amorphous calcium carbonate (ACC). However, in the altered carapace sample the Raman spectra showed a sharp band at 1086 $cm^{-1}$, which indicates well-ordered calcite. The chitin bands show a dramatically reduced intensity in the spectrum compared to the intensities of the fresh carapace sample. Typical decay products of chitin, i.e., polysaccharides, were identified by Raman spectroscopy in an area within the exocuticle. The Raman spectra of the altered specimen are clearly dominated by calcite, suggesting that ACC in the cuticle recrystallized to calcite during its alteration in a natural sediment. Such a calcite-bearing cuticle can be considered as “fossil” that has a high potential to withstand sedimentary processes for millions of years, at least as long as the surrounding sediment pore solution is saturated with respect to calcium carbonate.

Poster

## Mineralization of muscles and precipitation of crystal clusters during the decomposition of *Cambarellus diminutus* (Decapoda: Cambaridae) in freshwater

**Bastian Mähler, Thorsten Geisler, Jes Rust**

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It has been reported that mineralization experiments on decapods in artificial seawater resulted in the replacement of soft tissues by calcium phosphate, with the major source of phosphate being the carcass itself. In addition, crystalline structures of calcium carbonate were found, reflecting the fact that the exoskeleton of decapods contains calcite and amorphous calcium carbonate (ACC) distributed in cuticle layers. It is known that during the moulting phase of living crayfish, cuticle structures are destroyed and carbonate is transported through the hemolymphatic circulatory system from the cuticle to the stomach. Inside the stomach calcium carbonate precipitates to form gastroliths. After ecdysis is completed, gastroliths are partly re-dissolved for exoskeleton construction. Therefore, it can be assumed that calcium carbonate that precipitated as crystalline structures during the decay, might be provided by the carcass itself.

To study the taphonomy of decapods and related mineralization, ten dead individuals of *Cambarellus diminutus* were each placed and fixed by synthetic filter floss in 50 ml test tubes, half of which were filled with natural tank water and the other half with distilled water. The tubes were sealed and stored for 11 days at a constant temperature of 30°C. During the first four days, samples were scanned once per day and later after seven and 11 days using a micro-computed tomography (μ-CT) scanner. μ-CT data were used for three dimensional reconstructions of gastroliths and crystal clusters that formed during the decomposition process in both tank and distilled water. Volume measurements of 3D-surface CT-models revealed a general increase of crystal clusters and a contemporaneous volume reduction of gastroliths with progressive decay. The specimens that contained gastroliths showed a smaller total volume of these structures compared to specimens without gastroliths. To identify the crystal clusters and to study the mineralization and micro-texture of the altered exoskeleton, on day 11 altered crayfish samples were removed from the test tubes and prepared for Raman spectroscopy and scanning electron microscopy. Raman analyses clearly revealed that the crystal clusters consist of well-ordered calcite. We hypothesise that this difference in the total volume of calcite clusters in different individuals is due to the higher amount of ACC inside the endocuticle in individuals which were not in the moulting phase at the time of death. It follows that more ACC was available for the precipitation of crystal clusters during the decay in individuals which were in the inter-moult phase at the time of death.

Talk

## 99 my of morphological stasis in millipedes: CT scans, 3D-visualisation and gonopod reconstruction of a millipede family from Cretaceous Burmese amber (Diplopoda: Chordeumatida: Heterochordeumatidae)

**Leif Moritz, Thomas Wesener**

Zoological Research Museum Alexander Koenig, Germany

The mega-diverse yet understudied millipedes (Diplopoda) were among the first multicellular fully terrestrial organisms and play a fundamental role in terrestrial ecosystems as destruents and major soil-forming organisms. Despite their long evolutionary history, the fossil record of the Diplopoda is extremely poor; especially for the Mesozoic. Aside from the low number of known fossils, one problem is that a close study of the male copulation legs (gonopods) is needed for the secure assignment of a millipede specimen even to family-level. Only rarely can the gonopods of the few male fossils be studied in detail. The recent rediscovery of exceptionally well preserved arthropod inclusions in Cretaceous amber from Myanmar (ca. 99 mya), and the advent of modern micro-computed tomography (μCT) allow to widen our understanding of the Cretaceous millipede fauna. μCT does not only allow to study minute and obscured specimens within amber non-invasively, but also to remove taxonomically important structures and to compare them to extant representatives in detail. With such detailed comparisons several fossil specimens could be placed within extant genera, revealing morphological stasis in some millipede groups since at least the Cretaceous. Among these bradytelic millipedes is the enigmatic family Heterochordeumatidae, with at least two fossil species which can be placed within the two extant genera *Heterochordeuma* Pocock, 1893 and *Infulathrix* Shear, 2000. The Heterochordeumatidae are one of the few tropical Chordeumatida families, restricted to Southeast Asia and only known from the type-localities of the six extant species (Indonesia, Malaysia and Thailand). The highly hygrophilous Chordeumatida are the most short-lived millipedes, often with an annual life-cycle, and show great variations in body-shape. All previously known chordeumatidan fossils are from Baltic amber (ca. 35-23 mya) and belong to the extant family Craspedosomatidae. Thus, the described specimens are not only the first fossils of the family Heterochordeumatidae, but also the oldest records of the order Chordeumatida. The hypothesis, that the Chordeumatida are a fast evolving clade due to their extremely short life-cycle, can be refuted here, with representatives nearly resembling modern forms after ca. 99 my of evolution. Furthermore, Chordeumatida are highly hygrophilous, indicating the persistence of at least refugial mesic habitats in Southeast Asia throughout time since the Cretaceous, ensuring the survival of the Heterochordeumatidae and other arthropod groups found in Burmese amber. It can be expected that further studies of the Cretaceous millipede diversity will boost our understanding of the timing and pattern of millipede evolution tremendously.

Talk

## The New DFG Research Unit 2685: The Limits of the Fossil Record – Analytical and Experimental Approaches to Fossilization

**P. Martin Sander, Carole T. Gee, Thorsten Geisler-Wierwille, Jes Rust**

University of Bonn, Germany

The fossil record is the primary evidence for the history of life on Earth from its beginnings 3.8 billion years ago, but it is has become increasingly clear that our understanding of the material nature of fossils remains incomplete. Since the processes of fossilization shape the fossil record in a complex manner, we need to understand the limits imposed on the fossil record by fossilization processes if we are to understand the history of life. The last decade has opened up unprecedented opportunities for such research through the development of advanced analytical methods. However, such research needs to be conducted within an evolutionary framework in order to understand the evolutionary advantages and pathways that went into the selection of a particular biological trait in a fossil organism.

Advanced imaging methods applicable to fossils include radiological methods (micro-CT, synchrotron radiation CT) as well as 3D surface capture and imaging (e.g., photogrammetry, digital microscopy). New micro-analytical methods are equally promising in their application to fossils such as micro-Raman and IR spectroscopy, X-ray absorption spectroscopy (XAS), transmission electron microscopy (TEM), atom-probe tomography (APT), secondary ion mass spectrometry (SIMS), ion microprobe, laser ablation inductively-coupled plasma mass spectrometry (LA-ICPMS), nano-sized secondary ion mass spectrometry (NanoSIMS), as well as time-of-flight mass spectrometry (TOF-MS).

The DFG Researcht Unit 2685 “Fossilization” started work in January, 2018. The new research unit is centered around the Steinmann Institute, the Pharmaceutical Institute, the Kekulé Institute of Organic Chemistry, and the Institute of Medical Microbiology of the University of Bonn. Across nine projects, FOR 2685 is applying the latest in imaging and analytical technologies to the fossil record of plants, soft-bodied arthropods, and vertebrates with the objective of elucidating the material nature of fossils and the processes of fossilization. These include the process of bone fossilization, the silicification of plants and arthropods, the preservation of organic remains in bone, as well as the detection of organic remains in plants, arthropods, and vertebrate remains. In order to reach these aims, the results of carefully designed and reproducible fossilization experiments involving microbiological expertise will be linked to detailed investigations on naturally fossilized material. Based on this, we aim to establish proper research protocols across the disciplines and groups of organisms and ultimately to develop an integrative view of fossilization which will benefit evolutionary research as well as the geosciences.

**Talk**

## Age determation of fossil teeth and bones using the U-Pb decay system

**Michael Scheil**, **Frank Tomaschek, Paul Martin Sander, Markus Lagos, Torsten Geisler**

University of Bonn, Germany

Biogenic apatite, like in tooth enamel and dentine, and in bones, is the hardest material which can be produced by terrestrial vertebrates. The preservation probability is here much higher than in soft tissue and is, therefore, very interesting in terms of understanding the fossilization process in general. During fossilization, bone collagen decays and hydroxyapatite is replaced by the more stable fluorapatite. Bone often incorporates uranium shortly after death of the individual, which decays into radiogenic lead isotopes. This radiometric clock can be used to date the biogenic apatite using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

A first set of biogenic apatite samples comprised two polished core sections of sauropod bones from the Upper Jurassic Morrison Formation (Kenton Quarry, Oklahoma). *In situ* laser ablation analyses were targeted on bone apatite and diagenetic calcite fillings of the vascular canals. Uranium concentration was typically very low for the diagenetic calcite (< 1 ppm), whereas the bone apatite contained U contents of > 100 ppm. In a Tera-Wasserburg diagram, the measured isotopic ratios plot along a mixing line towards common lead composition as determined by the calcite data. Both samples yield U-Pb ages of about 25 to 35 Ma, substantially younger than the Late Jurassic chronostratigraphic age (~ 150 Ma). Consistent linear arrays and similar ages suggest that some geologic significance may be assigned to the radiometric age information. Possible correlations with regional tectonic events, however, are currently not known.

A second set of Upper Jurassic biogenic apatite samples was compiled from carbonate beds in the Langenberg Quarry, Germany. These beds were steeply inclined by the Northern Harz Boundary Fault in this quarry. Samples comprise sauropod bones and teeth. The most striking observation is a contrasting behavior of the U-Pb systems of tooth enamel and dentine, respectively. A least-squares regression for dentine analyses yields ages about 80 Ma, assuming common lead from sediments in the pulp cavity. In contrast, enamel from the same tooth was found to be by far too radiogenic, reflected by apparent U-Pb ages that are much older than the Jurassic. While dentine could have been completely reset during rejuvenation of the Harz Boundary Fault, uranium might have contemporaneously and selectively been lost from enamel. Further research, however, is certainly needed to understand which factors influence the U-Pb system of fossil biogenic apatite.

**Poster**

## Preliminary results to the organic phase (extracellular matrix, osteocyte, blood vessel) preservation in dinosaur bone: imaging the organic remains in fossilized bone

**Kayleigh Wiersma**[1], **Sashima Läbe**[1], **Marie-Claire Koschowitz**[1], **Markus Lambertz**[2], **P. Martin Sander**[1,3]

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Hard tissues, such as bones and teeth, fossilize well, and provide the exceedingly rich fossil record of vertebrate evolution. In addition to their shape, the histological structure of bones is also preserved. Bone is a composite material consisting of an inorganic phase (IP) of about 70% by volume and an organic phase (OP) of 30% by volume. The OP consists mainly of collagen and is also known as the extracellular matrix (ECM).

Since the 1970s, soft tissues and bone proteins have been detected in fossilized dinosaur bone, contradicting the previous belief that the OP of bone is completely destroyed during fossilization. Only recently, the discovery has been made that organic remains such as osteocytes, blood vessels and sometimes ECM can be liberated from the fossilized bone by carefully dissolving it using weak organic acids. This discovery, however, led to a controversy over the organic remains being original soft tissue preservation or biofilms produced by bone-degrading bacteria, and the overall realization that fossil bone remains poorly characterized.

The aim of this research is to first test the hypothesis that the organic phase represents altered ECM, osteocytes, and blood vessels as opposed to fossilized biofilms. The second aim is to develop hyptheses about the processes leading to the preservation of the OP and its degradation products and thus the conditions that are conducive to OP preservation.

To test these hypotheses, large sample of great temporal and environmental range was assembled. The bone samples were carefully dissolved by EDTA over a period of days and weeks, liberating osteocytes, blood vessels and some ECM in the residue. After the dissolving process, the residues were stored in a buffer solution. Microscope slides of the residue were created by washing the organic remains with ethanol, isopropyl alcohol, and xylene, and sealed with a fixing agent. Further work includes the analysis of the sediment and bone IP, analysis of OP using scanning electron microscopy and transmission electron microscopy, and experimental work on bacterial degradation.

**Talk**

## Deciphering the organic constituents of fossils using modern analytical methods

**Klaus Wolkenstein**

Geoscience Centre, University of Göttingen, Germany

Apart from mineralized remains such as bones and shells, many well-preserved fossils contain small amounts of organic compounds that can provide valuable information on former life. General chemical characterization of fossil organic materials has commonly been performed by Raman spectroscopy, IR spectroscopy or destructive methods such as pyrolysis-gas chromatography-mass spectrometry. However, although the analysis of organic remains from fossils still is challenging, the development of advanced analytical methods now allows the detailed determination of these organic remains.

Several almost intact metabolites have been identified in fossil invertebrates and vertebrates in recent years. Mixtures of extractable compounds can be separated and analyzed by high-performance liquid chromatography-mass spectrometry (HPLC-MS), and high-resolution time-of-flight mass spectrometry provides molecular formulae of the compounds. The identification of fossil organic compounds usually requires comparison to reference compounds. Because completely unknown compounds cannot be compared to a reference, the identification of such compounds is much more difficult. The direct structural identification of individual organic compounds from fossil organisms by conventional nuclear magnetic resonance (NMR) spectroscopy was not possible until recently due to the tiny amounts of preserved material and the inherently low sensitivity of NMR. However, using the new methodology of microcryoprobe NMR spectroscopy the structural identification of previously unknown Jurassic pigments and even Precambrian molecular fossils could be accomplished based on microgram amounts.

# Topics 12: Applied and industrial micropalaeontology

## 12a) Reconstructing lost worlds – applications of microfossils

Talk

### Benthic and planktic foraminiferal morphogroups from the pre-Messinian of Sardinia and Sicily – significance for palaeoecological reconstructions

**Anne Förster, Olaf Elicki**

TU Bergakademie Freiberg, Germany

Foraminifera represent a very useful fossil group for the interpretation of ancient marine environments and are widely used proxies for palaeoenvironmental and palaeoceanographic reconstructions. For that reason, the concept of morphological groups has increasingly been applied in the last decades. Morphogroups are independent of a detailed species level taxonomy, which allows the achievement of palaeoecological results within comparatively few time. During this study, this approach has been applied to pre-Messinian sediments from Sardinia and Sicily to test its significance for concluding environmental changes immediately prior the Messinian Salinity Crisis (MSC).

During the Tortonian and Messinian, the Mediterranean region experienced profound oceanographic and environmental changes, culminating in the MSC. Whereas the ecological turnovers during this drying interval are well investigated, related phenomena in the emergence of the crisis are poorly known. Therefore, two different environments from immediately pre-Messinian deposits of the Mediterranean have been investigated: shallow marine grey marls and overlying limestones, sandy marls and fine sands (Sinis Peninsula, Sardinia) as well as deep marine whitish/grey marls with sapropelitic layers (Monte Gibliscemi, Siciliy).

A total of 74 sediment samples were taken and analyzed regarding their content of foraminifera. Both successions delivered a diverse foraminiferan microfauna which was investigated by using the concept of morphological groups. Whereas this concept (originally introduced by Jones and Charnock in 1985) is already used especially in studying benthic and mostly agglutinated foraminifera, we transferred this approach to late Miocene planktonics to evaluate their potential for ecological studies.

It can be shown that the determined morphological groups and their quantitative relations reveal a useful approach to evaluate and to compare late Miocene ecologically determined foraminiferan assemblages of different areas and stratigraphic positions without using detailed taxonomy. Preliminary results suggest an unexpected morphological diversity among the benthic foraminifera within a succession of petrographic monotonous marls. Based on their distribution it was possible to subdivide this problematic succession ecostratigraphically by using 12 morphogroups (6 of them indicating an epifaunal and 6 an infaunal mode of live). For the planktic associations we tried a subdivision into spinose versus non-spinose and keeled versus non-keeled individuals, but the first results show only minor spatial differences.

In general, the morphological architecture of benthic foraminiferan assemblages seems to provide a useful tool for the recognition of pre-MSC environmental changes in the marine realm. Regarding planktic foraminifera, a detailed taxonomical investigation seems to be inevitable.

Talk

### Re-evaluation of benthic foraminifera as indicators of bottom current strength

**Patrick Grunert[1], Ángela García Gallardo[2], Antje H.L. Voelker[3], Isabel Mendes[4], Werner E. Piller[2]**

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In the face of recent global warming, paleoceanography and paleoclimatology provide fundamental contributions to our understanding of ocean-climate dynamics through reconstruction of ocean circulation under different climatic regimes. Well-calibrated proxy methods are at the core of these research efforts. Contourite drift systems (CDS), depositional environments under persistent bottom current activity, provide formidable testing grounds. In the Iberian Margin CDS, abundances of distinct benthic foraminifera (often referred to as the "elevated epifauna") are controlled by the strength and nutrient load of bottom currents. Abundances of this bottom current fauna (BCF) in sediment cores have thus been used to reconstruct variations in Mediterranean Outflow Water in the past. However, new faunal and geochemical data from Pliocene-Pleistocene contourites drilled during IODP Expedition 339 strongly indicate that the method is prone to be compromised by taphonomic processes, in particular downslope transport in areas with an unstable continental margin such as the southern Iberian Peninsula. Here we present first results from our ongoing re-evaluation of the BFC that aims towards a better understanding and improvement of this potentially powerful proxy method.

Our new data come from Pliocene and Holocene samples collected along the southern Iberian Margin, a key area for the establishment of the BCF proxy. The results demonstrate that episodic downslope transport may bias abundances of the BCF by delivering BCF taxa with a broad bathymetric range such as *Cibicides lobatulus* and *C. refulgens* to greater water depths. Abundances of these species should thus be treated with caution when co-occurring with other allochthonous shelf taxa. Other BCF species such as *Planulina ariminensis* are restricted to slope environments and provide a more reliable indicator of bottom-current strength.

In a next step, we plan to expand our research area to other CDSs in the North and South Atlantic. For the first time, biogeographic patterns and the applicability of the BCF proxy beyond the Iberian Margin will be evaluated from a comprehensive set of surface samples. Combined with samples from sediment cores, taphonomic biases and novel approaches to overcome them will be examined.

**Poster**

## High resolution facies evolution in the early Miocene of the North Alpine Foreland Basin, with a new ostracod fauna contribution

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The North Alpine Foreland Basin (NAFB) served as the depositional basin for the Molasse sediments from the early Oligocene until the late Miocene. In the early Miocene (17.5 Ma, late Burdigalian) environmental conditions changed from marine to brackish and the sedimentation of the Upper Marine Molasse was succeeded by the deposition of the Upper Brackish Molasse. During this period, two basins developed within the formerly continuous Molasse basin of southern Germany, giving rise to the brackish sediment sequences now known as the Oncophora Formation in the East and the Kirchberg Formation in the West.

However, correlations between the Upper Brackish Molasse of the two basins are still problematic, mainly because the ages of the present formations cannot be precisely constrained, and also because it is not clear whether the faunas of the two basins were interconnected. As a result, different paleogeographic scenarios have been proposed, but a detailed reconstruction of the relevant developments is still lacking. Our objective was to study faunal similarities between the upper Oncophora Fm and the Kirchberg Fm, and investigate salinity changes throughout the upper Oncophora Fm, with a view to elucidating the regional paleogeography. The study site in southeast Bavaria was an 8-m-thick section comprising sands, silts and marls. Washing and sieving of 13 sediment samples yielded 500 microfossils, on which taxonomic studies, statistical analyses (cluster analysis, non-metric multidimensional scaling) and oxygen- and carbon-isotope measurements were conducted.

About half of the microfossils could be identified to species level. The taxonomic results, as well as the statistical analyses, indicate that the fossil assemblage from the upper Oncophora Fm clearly differs from that of the Kirchberg Fm. Moreover, it contains a previously unknown ostracod fauna comprising two marine and two brachyhaline species, which signals a distinctive increase in salinity in the uppermost part of the section, in a facies which was hitherto believed to represent a freshwater environment. We conclude that, at least during the interval represented by the upper Oncophora Formation, the Oncophora basin was spatially or chronologically separated from the Kirchberg basin. Consequently, the rise in salinity cannot be explained by the transgression event that led to the deposition of the Kirchberg Fm. The different facies in the Oncophora Fm probably evolved in a dynamic delta environment, in which different facies co-existed over small spatial scales.

**Poster**

## Foraminiferal-based reconstruction of changes in thermocline structure across the MIS 30/29 and MIS 22/21 transitions at IODP Site U1313

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The Mid-Pleistocene Transition (MPT, 1250-600 ka, Marine Isotope Stages (MIS) 35-15) is characterized by the change from a 41 kyr obliquity-paced glacial/interglacial rhythm to the present-day 100 kyr eccentricity-like glacial/interglacial cycle. This transition from obliquity to eccentricity occurred without obvious changes in the orbital configuration, hence, the paleoclimatological processes at work remain uncertain. Notably, overall cooling during the MPT was accompanied by an increase of the glacial ice volume in the northern hemisphere, demanding a process that delivers moisture into high latitudes under cold background conditions. In this respect, the North Atlantic Subtropical Gyre (NASG) might have played a pivotal role as this wind-driven ocean circulation system transports moisture and heat into the higher-latitude North Atlantic. Growing glacial ice shields over the course of the MPT distinctly modified the wind-fields and should have altered the intensity and spatial extend the NASG and thus northward heat transport. In addition, enhanced production of saline Mediterranean Outflow Water (MOW) during the MPT could have enhanced the salinity budget of the NASG, fueling northward heat and salt transport.

To study the impact of ice-sheet growth and MOW dynamics on the NASG, we investigated the thermocline structure at North Atlantic IODP Site U1313 (41.00°N, 32.57° W), located at the northern boundary of the NASG, for the transitions between MIS 30/29 and MIS 22/21. The selected intervals are peculiar as they show an unusually high subsurface temperature (subT) preceding surface warming and ice-sheet decay (reflected by benthic foraminiferal $\delta^{18}O$) by almost 20 kyr arguing for an enhanced subsurface heat transport. To

constrain the origin of the subT warming we compare δ$^{18}$O analyses of planktic foraminifera dwelling in the shallow and deep thermocline (*Globorotalia inflata* and *Globorotalia crassaformis*, respectively) with sea-surface temperature (SST) and global ice-volume changes. The temporal relation of hydrographic changes in the upper water column will provide information about whether the warming primarily originates from thermocline deepening by enhanced wind forcing (in this case the warming signal should propagate from the surface to the deeper thermocline) or from enhanced MOW production, which should initiate warming of the deep thermocline first. The results will thereby contribute to our understanding of the processes forcing heat and moisture distribution in the North Atlantic realm during a critical interval of Pleistocene climatic evolution.

**Poster**

## Biometric analysis of modern miliolid benthic foraminifera as revealed by high resolution microtomography

**Janine Könen**

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Shells of shallow marine benthic foraminifera preserve high-resolution records of environmental conditions. The growth conditions are recorded, for example in variations of the stable isotope composition across shells, in geochemical proxies (Cd/Ca) or in growth rates during ontogeny. We have applied high resolution X-ray micro-computed tomography (Micro-CT) to a suite of modern benthic miliolid foraminifera (biloculine, triloculine, pseudotriloculine, quinqueloculine, spiroloculine & planispiral) to quantify biometric test features by means of three-dimensional images and to relate them to environmental and oceanographic variables that shape the foraminiferal niche space. Micro-CT is a novel technique for generating three-dimensional images with submicron resolution to provide a virtual non-invasive insight into opaque objects. The method enables a visualization and computational measurements of calcified test parts and hollow parts of the chambers (chamber lumina) from the proloculus to the final chamber. Biometric measurements of individual chamber lumina and calcified test volumes allow the quantification of volume accretion and growth patterns during ontogeny. Volumetric growth rates of chamber lumina and growth functions were computed and related to environmental parameters to assess the response to environmental forcing.

Quantitative volume computations of miliolid foraminiferal growth revealed exponential growth patterns for all investigated species. It indicates that specific morphological features of the embryonal apparatus shape both the volumetric chamber shape and growth pattern during ontogeny. We also found that rates of volume accretion are intrinsically linked to the mode of coiling and arrangement of chambers in non-symbiont bearing smaller miliolids. Growth patterns in symbiont-bearing *Peneroplis planatus* show that both depth and light constrain rates of volume accretion of calcified test parts, but has no effect on the cellular growth. Micro-CT applications and shell parameter quantifications provide powerful proxies to infer conditions of the past.

**Poster**

## New insights into the Famennian of the Minervois Nappe (Ravin de la Fontaine de Santé, southern France)

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The Montagne Noire is one of the classical regions for the study of Upper Devonian stratigraphy and facies in Western Europe. That is why three Global Stratotype Sections and Points (GSSP's) have been ratified by the IUGS (International Union of Geological Sciences) in this area: Col de Puech de la Suque (Middle/Upper Devonian), Coumiac (Frasnian/Famennian), and La Serre trench E' (Devonian/ Carboniferous).

The Montagne Noire represents the most southern and external part of the Massif Central within the Variscan Orogenic Belt (Aretz et al. 2016). Its sedimentary successions belong to nappes, which were delivered from the north (Engel 1981). In contrast to the well-studied, non-metamorphic (par)autochthonous units, e.g. the Faugeʻres Nappe, Mont Peyroux Nappe (including the detached Pic de Bissous Block), and the olistolithic "Cabriéres Klippen" in the east, as well as Pardailhan Nappe in the west, the successions of the Minervois Nappe in the west are poorly investigated so far, although they offer tremendous research potential. Of special interest are the search for global event levels, and a comparison of local sea level change, conodont biofacies fluctuations and diversity in comparison to the other nappes.

The Fontaine de Sante' section is located ca. 500 m to the northeast of Caunes Minervois, within a small valley south of the road to the Rocamat marble quarry. It was first described by Boyer et al. (1968). Tucker (1974) and Bourrouilh (1981) revised the sedimentology, Crilat (1983) and Bourrouilh et al. (1998) published sparse conodont data, which provided a first, rough but incomplete biostratigraphy. Due to the current outcrop conditions, our re-investigated succession was split into two parts. We measured both sections (A and B) bed-by-bed. Until now, 32 of 87 possible conodont layers were sampled. Section A possesses a thickness of ca. 6.25 m and consists of grey to reddish-grey flaserkalk, overlain at the top by 1.5 m by reddish micritic flaserkalk ("griotte facies"). The main Section B, ca. 15 m thick, contains the entire sequence from "griotte facies" to "vraie griotte" and "supragriotte". In contrast to Section A, orange clay seams occur within the "griotte facies", whereas the "vraie griotte" consists of red micritic nodular limestones; the "supragriotte" is developed as red to grey micritic flaserkalk. First conodont data suggests that Section B ranges from the *Palmatolepis termini* / *Pa*. *glabra prima* (middle part of the lower Famennian) to the *Pa*. *marginifera utahensis* zones (middle part of the middle Famennian).

Poster

## Vagile echinoderms from a Carboniferous pelagic environment – Evidence for the antiquity of the modern deep-water fauna

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Echinoderms are important constituents of the modern deeper water macrobenthos. Asteroids, ophiuroids, holothuroids and crinoids abound in dark, low-temperature environments from deep outer shelf to abyssal plains. Herein we present a diverse vagile echinoderm fauna from Serpukhovian (late Mississippian) pelagic limestones of the Cantabrian Mountains (NW Spain). It indicates the common occurrence of the group in deep-water environments already in the late Palaeozoic and underlines the long-lasting history and conservative nature of modern deeper water echinoderm communities.

The Spanish fauna consists of isolated ossicles derived from acid-etched residues of limestones from sections of the uppermost Genicera Formation (= Alba Formation, latest Tournaisian–Serpukhovian) in the surroundings of the Bernesga valley (N León). The Formation is widespread throughout the Cantabrian Mountains. Facies analogues from the Pyrenees, the Catalonian Coastal Ranges and Menorca testify a huge pelagic realm in the Iberian part of southern Armorica. Most of the Genicera Fm. consists of condensed nodular limestones (“griotte”) yielding a diverse pelagic fauna. Prevailing are goniatites, cyathaxonid corals, trilobites characteristic of the Kulm facies, conodonts and arenaceous foraminifers. Except for the rare monospecific occurrence of the long-stemmed inadunate crinoid *Balearocrinus cantabricus*,macroscopic echinoderm remains are restricted to crinoid stem fragments and indeterminable ossicles; crinoid ossicles and transverse sections of echinoid spines are also seen in thin sections. Our microfauna is the first record of determinable non-crinoid echinoderms from the Genicera Fm. The carbonate microfacies of the samples supports the deeper water origin of the fauna. Bioturbated, in part pure radiolarian mudstone to sparsely packed, bioturbated bioclastic wackestone without any shallow-water components prevail; microbialites occur. Globochaete packstone and debrites indicate intrabasinal redeposition. The deeper water nature of our echinoderm fauna is of special relevance, as further Carboniferous occurrences are only known from shallow-water carbonate platforms.

The recovered echinoderm ossicles belong to holothuroids, ophiuroids, ophiocistioids, echinoids and crinoids. Among holothuroids remains of both stem clades occur: Apodida is represented by the typical apodan wheel-shaped ossicles (*Langepis*, *Rotoides*); Actinopoda by sieve plates (*Eocaudina mccormacki*, ?*Eocaudina* sp., *Spicatocaudina spicata*) and indeterminate table plates. Within the Actinopoda, a cross-shaped ossicle attributed to *Tetravirga* represents the Elasipodida. Among ophiocistioids *Linguaserra* cf. *ligula* and a slender new species of *Linguaserra* was found. Further ossicles might be ophiocistioid perradialia. Ophiuroids yielded characteristic skeletal elements of *Furcaster*, including a new species of the paragenus *Calclyra;* a distinct lateral arm plate was attributed to the order *Pectenura*. Echinoids and crinoids remained untreated.

Poster

## Micro- and Macrofossils as indicators of Early Holocene palaeoenvironmental changes in the northwestern Saudi Arabia

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The reconstruction of palaeoclimatic changes is a key to understand landscape change, prehistoric human migration and settlement, in particular within sensitive arid environments. Whereas there are several Late Pleistocene to Holocene climate records from the Sahara, the Levant, and the southern Arabian Peninsula, Northern Arabia is poorly known so far. The continental sabkha of Tayma (27°38’N, 38°33’E) is one of very few North Arabian sites, where landscape changes are recorded in a laminated lacustrine sequence.

The early to mid-Holocene palaeo-lake of Tayma, 250 km away from the Red Sea and about 800 m above sea level, yields a fossil fauna almost completely composed of the euryhaline barnacle *Amphibalanus amphitrite,* two gastropods (*Melanoides tuberculatus*, *Hydrobia* sp.), four foraminifer species (*Ammonia tepida, Quinqueloculina seminula, Flintinoides labiosa, Trichohyalus aguayoi*), and the brackish water ostracod *Cyprideis torosa*, beside very rare freshwater ostracods. Only the smooth shelled morphotype of *Cyprideis torosa* occurs. The association indicates a large athalassic brackish water lake with temporary freshwater inflows. All species documented originate in the marginal marine environment of the Red or Mediterranean Sea within the intertidal zone and hence they are adapted for strong environmental changes. Morphological and taphonomical analyses on *Cyprideis torosa* (i.e., sieve pores, population structure, preservation) and test malformations on the foraminifers reveal habitat types and its changes for sediment cores and sections from the center and the margins of the lake basin. The lake evolution starts immediately with saline conditions. At its maximum, the lake had a perennial regime, brackish to seasonally even hypersaline conditions, a depth of up to 16.7 m and covered a minimum area of c. 22 km$^2$. The increasing salinity at the younger part of the sections confirms a climatic shift to drier conditions during the mid-Holocene.

Poster

## The environs of Elaia's ancient harbour – a reconstruction based on microfaunal evidence

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During Hellenistic and Roman times, Elaia, the harbour city of ancient Pergamum, was an important place of trading and traffic in the eastern Mediterranean Sea. Intense mercantile and military activities are documented by literary sources and archaeological evidences. The aim of the present study is to reconstruct the history of Elaia's harbour within the context of coastal evolution. For that purpose, a sediment core was drilled in the centre of the ancient closed harbour. As indicated by a diverse marine microfauna, the site's evolution started about 7700 years ago in fully marine conditions and with a predominance of phytal taxa like *Asterigerinata mamilla*, *Rosalina macropora* and *Lobatula lobatula*, followed by a lagoonal soft bottom assemblage, containing species like *Ammonia tepida* and *Haynesina germanica*, mirroring the construction of the breakwaters in Hellenistic times. Silting up caused the abandonment of the harbour in late Roman times. Whereas Foraminifera are more abundant during the marine period and can be used together with Ostracoda, the latter are more valuable proxies recording the perishing of ancient coastal harbours because ostracods are more abundant in brackish water and coastal pond habitats and occur in freshwater bodies.

Talk

## Infaunal sea cucumbers (Echinodermata: Holothuroidea) from the Jurassic of Europe

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Molpadid sea cucumbers are more or less sausage-shaped marine echinoderms of medium size, with the posterior end usually tapering to form a distinct tail. Members of this actinopod clade typically live buried or in depressions in muddy, silty or sandy substrates, from the subtidal zone down to hadal depths. In suitable habitats they can form populations of hundreds of specimens per $m^2$, making them important bioturbators. Fossil members of the Molpadida are lesser known than species of other holothuroid groups (e.g. Apodida). However, isolated body-wall ossicles are frequently reported from Jurassic strata onwards, but sometimes misinterpreted. Articulated molpadid body fossils are missing so far, but isolated elements of the calcareous ring are distinct and present in the Mesozoic/Cenozoic fossil record. Unfortunately, these elements were often overlooked or neglected by palaeontologists/micropalaeontologists.

Here we present, for the first time, a few larger assemblages of molpadid sea cucumbers from various Jurassic strata (Sinemurian, Callovian, Oxfordian) of Europe (Germany, Luxembourg, Switzerland, U.K.), including several new taxa. All of these are based on distinct radial and interradial plates of the calcareous ring. Due to a detailed comparison with extant forms, we are able to determine the exact position of all isolated plates within the calcareous ring (dorsal *versus* ventral). These new records have novel implications for the evolution and phylogeny of sea cucumbers as well as for the understanding of the Mesozoic „infaunalization" of Holothuroidea, and echinoderms in particular.

Talk

## Oxygen isotopes and Mg/Ca of larger benthic foraminifera: Potentials and pitfalls

**Pratul Kumar Saraswati**

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The larger benthic foraminifera (LBF) contribute significantly to the modern reef and shallow-marine carbonates. They were also the major producers of platform carbonates in the Permian, Cretaceous and Cenozoic times. It is pertinent to ask, what makes them biologically superior for their dominance in certain environments of the present day and during certain periods in the geologic past? The biology and ecology of the LBF are known from observations in modern environments. A further understanding of the life history and paleoecology of the fossil LBF would require the development of proxies preserved in their carbonate tests. The two geochemical proxies, $\delta^{18}O$ and Mg/Ca, widely used for estimation of seawater temperatures, are studied in the living LBF from Akajima (Pacific Ocean) and Lakshadweep (Indian Ocean) to assess their potential in interpreting the life history of the foraminifera. The results obtained so far suggest that oxygen isotopes are precipitated in near equilibrium with seawater and thus an ontogenetic record of $\delta^{18}O$ has potential applications in estimating the temperature tolerance of species, lifespan, the season of reproduction and relative depth distributions. The use of Mg/Ca for similar applications is rather suspect. There is a large difference in Mg/Ca of species calcified under the same ecological conditions and in most species, Mg/Ca is not correlated with seawater temperatures. There is also a high order of intra-test spatial heterogeneity in the distribution of Mg and Ca. It appears that while vital effect has a little role in oxygen isotopic composition of the LBF carbonates it influences the Mg/Ca in a major way. The relatively large size and longer lifespan of this group of foraminifera have several advantages in retrieving palaeobiological information but it is also of major concern in calibration of the geochemical proxies. There is compositional averaging in whole-specimen analysis due to the growth of LBF over months to a year or more. There is also an uncertainty about the calcification temperatures, the LBF being symbiont-bearing are likely to record higher of the diurnal seawater temperatures due to photosymbiosis-enhanced calcification in day-time.

Talk

## Biofacies analysis of agglutinated foraminifers along an Upper Devonian transect from Central Europe to North Africa

**Anna Saupe[1], Sven Hartenfels[2], Ralph Thomas Becker[1]**

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In the Famennian (Upper Devonian), agglutinated foraminifers were widespread, particularly in hemipelagic shelf regions with reduced siliciclastic influx. As a M.Sc. project of the first author, pelagic limestone successions were studied along a palaeolatitudinal transect, which represents different palaeoclimatic zones. It runs within the Variscan Sea from the southern shelf of Laurussia to the northern shelf of NW Gondwana. Studied outcrops are situated in the Rhenish Slate Mountains (Oese, Germany) belonging to the southern palaeo-tropics, the Thuringian Slate Mountains (Kahlleite East, Germany) and the Montagne Noire (Col des Tribes, Southern France), representing a transitional zone (Armorica Terrains), and in the Moroccan Meseta (Ziyyar I) assigned to the palaeo-subtropics. Investigated successions concentrated on the hypoxic and transgressive Lower and Upper *Annulata* Events and the Dasberg Crisis. In the conodont scale, all studied sections range from the *Palmatolepis marginifera marginifera* (= Lower *marginifera*) to the *Bispathodus aculeatus aculeatus* (= Middle *expansa*) Zone.

Around 13.500 picked foraminifers belong to nine genera and 32 species. The elongated, incrusting genus *Tolypammina* stayed evenly distributed in all successions. It is a representative for an “upper shelf margin and shallow water setting” sensu Gutschick & Sandberg (1983). It shows the highest abundance (85%) in the southern palaeo-tropics represented by Oese. The elongated, non-attached genus *Hyperammina* is sparse before the *Annulata* Events but became more frequent afterwards, but only for a short term, and especially in the transitional zone (ca. 90%). According to Gutschick & Sandberg (1983), it occurs at the “middle to lower continental slope”. This indicates slightly deeper post-event conditions at all sections, but with good oxygenation since *Tolypammina* is still prevalent. *Hyperammina* replaces almost all globular foraminifers after the events, such as *Thurammina*, *Psammosphaera*, *Pseudastrorhiza,* and particularly the attached subglobular forms *Tholosina* and *Webbinelloidea*. They occur in higher energy settings before the black shale events (Gutschick & Sandberg 1983), with high abundances in the transitional zone and the palaeosubtropics (50-80 %). In the palaeo-tropics at Oese, they amount only to an average of 10-15%. A decrease of globular taxa can be observed around both *Annulata* Events at all locations. It is followed by a slight recovery and the return of local Lazarus taxa at the European successions and lasting local extinctions in the palaeo-subtropics at Ziyyar I.

### References

Gutschick, R. C. & Sandberg, C. A. (1983): Mississippian Continental Margins of the Conterminous United States. – Society of Economic Paleontologists and Mineralogists, Special Publication, **33**: 79-96.

Talk

## Applicability of benthic foraminifera in marine paleoclimate research

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Our present understanding of past changes in climate and ocean circulation is to a large extent based on information from marine sediments. These sediments contain a variety of microfossils, which record (paleo)-environmental information through their floral and faunal assemblages and geochemical composition. In this context, benthic foraminifera have been widely used in the reconstruction of changes in organic matter fluxes, oxygen content, sea level and bottom currents. In intertidal and shallow neritic environments the distribution of foraminifera is closely related to gradients in salinity, pH, grain size, and tidal range, allowing for the characterization of different ecological niches. Salt-marsh foraminifera show a distinct vertical zonation relative to the tidal frame making them precise indicators for past relative sea-level changes. Various transfer functions have been developed to quantify the relationship between modern foraminifera and tidal level and submergence frequency, which are then applied to foraminiferal assemblages in fossil records. Recently, similar quantitative approaches have been extended to shelf environments allowing for the reconstruction of relative sea-level changes over larger depth intervals and longer time scales. In deep-sea environments, benthic foraminifera provide information on the bentho-pelagic coupling and therefore respond to changes in climate and ocean circulation. The microhabitat structure, diversity and density of benthic foraminifera are closely related to surface productivity and corresponding organic carbon fluxes. Although these relationships are increasingly well understood, widely applicable transfer functions for trophic reconstructions are still missing. Recently, various indices have been developed for the assessment of oxygen concentrations in the bottom water providing at least semi-quantitative data. In addition, accurate quantitative oxygen reconstructions have been established using multi-species benthic foraminiferal stable carbon isotopes. The accumulating knowledge on benthic foraminiferal ecology and increasing number of available data on the distribution of modern species and faunas provokes the development of reliable transfer functions in the near future.

Talk

## Early Permian radiolarians from Phi Phi Island, Southern Thailand

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The stratigraphic succession and global correlation of Permian radiolarian zones is now firmly established and here we describe the first radiolarians from the Permian carbonate formations of Thailand and assess their stratigraphic, palaeogeographic and palaeoclimatic significance.

The carbonate mudstone succession and the overlying thin-bedded, silicified limestone, chert and limestone from Phi Phi Island constitute the uppermost part of the Kaeng Krachan Group and the lowermost part of the Ratburi Group. This mudstone contains species of the radiolarian *Pseudoalbaillella*, a few *Mesogondolella* conodonts and some sponge spicules. Radiolarians are characterized by an abundance of *Pseudoalbaillella aidensis* and other species include *Ps. elegans, Ps. fusiformis,Ps. Lomentaria*, *Ps. longtanensis*, *Ps. m. scalprata*, *Ps. m. postscalprata*, *Ps. m. rhombothoracata*, *Pseudoalbaillella u-forma* m.I, *Pseudoalbaillella u-forma*- m.II, *Ps.* cf. *aidensis, Ps.* cf. *elongata, Ps.* cf. *lanceolata*, *Ps.* cf. *lomentaria,Ps.* cf. *longicornis, Ps.* cf. *longtanensis, Ps.* cf. *ornata, Ps.* cf. *simplex*, *Ps.* sp. A, *Ps* (?) sp, and *Ps*. spp. *Pseudoalbaillella aidensis*is the most important species in the Kungurian *Pseudoalbaillella longtanensis* Zone (Nishimura & Ishiga, 1987).

The siliciclastic Kaeng Krachan Group is approximately 900 m thick and was previously known as the Phuket Group. It and correlative formations extend from northern Malaysia through western Thailand to Myanmar and Baoshan in Yunnan Thailand. Its constituent facies are similar to typical Gondwana glacial sediments. On Phi Phi Island, Krabi Province, peninsular Thailand brachiopods are found 65 m below and also immediately below the Ratburi Group carbonates. The lower fauna consists of a cool-water brachiopod fauna of late Asselian to early Sakmarian age and the upper fauna consists of *Streptorhynchus* and *Bandoproductus*. On the Thai mainland, on nearby islands and in Myanmar, brachiopod faunas from the uppermost Kaeng Krachan Group and correlates have been assigned to the *Spinomartinia prolifica* assemblage described by Waterhouse et al. (1981).

These stratigraphic and palaeogeographic reports and the occurrence of a high abundance but low-diversity radiolarian fauna suggests restricted physical conditions along a cool, upwelling, deglaciating continental margin.

Talk

## Reworked conodonts from the Lower Permian carbonate turbidites in the Inthanon Terrane, Northern Thailand and their tectonic significance

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Northern Thailand has from west to east been divided into the Sibumasu, Inthanon, Sukhothai, terranes and Nan Suture. The Inthanon Terrane has been interpreted as autochthonous platform sediments of the Sibumasu Terrane overlain by thrusted allochthonous oceanic sediments and mafic igneous rocks. The allochthonous carbonates contain warm water Carboniferous-Permian faunas in contrast to the cool water faunas of the Permian carbonates of the Gondwana derived Sibumasu Terrane (Ueno and Charoentitirat, 2011). A carbonate turbidite succession near Lamphun, to the south of Chiang Mai in Northern Thailand in the Inthanon Terrane contains Upper Devonian, Lower Caboniferous and Lower Permian conodonts. The turbidites, with common graded, convolute and plane laminations, are thin to medium bedded and overlie a 2 m thick basalt and a ribbon chert succession. Conodonts from the turbidite sequence include *Gnathodus raisae, Idiognathoides tuberculatus, Lochriea glaber, Lochriea*sp., *Mesogondolella* cf. *monstra, Mesogondolella* cf. *arccuata, Mesogondolella* cf. *gutta, Neognathodus* cf. *symmetricus, Palmatolepis* sp., *Streptognathodus* sp. and others.

Previous interpretations of this locality have been as a carbonate seamount (Feng et al., 2008) or as blocks within an accretionary prism (Metcalfe et al., 2017). We interpret these mixed faunas as a result of eroded carbonate grains from pre-existing strata of a platform or continental shelf margin. The German Geological Mission to Thailand also reported several localities in Northern Thailand where Devonian conodonts reworked into Carboniferous and Permian limestones (Stoppel *in* Baum et al., 1970). The underlying basalt is alkaline to sub-alkaline and is either a within-plate basalt or an OIB (Feng et al., 2008). None of these data provide strong support to the models of Feng et al, Ueno and Choroentitititrat and Metcalfe et al but may suggest deposition on a carbonate platform and its margin with the basalts being formed in a north-south rift or embryonic ocean.

An alternative model is to have both terranes rifted off the margin of Gondwana where they had similar successions of Cambrian siliciclastics and Ordovician limestones. Inthanon rifted off, possibly in the Silurian, and moved into the Palaeotethys followed by the Sibumasu Terrane in Early Permian. By the Pennsylvanian, Inthanon had reached the subtropics but Sibumasu was still part of glacial Gondwana. The two terranes were reunited along the Mae Yuam suture during Late Triassic which was strongly modified in the Cenozoic. The Sukhothai Volcanic Arc developed along the present eastern margin of the Inthanon Terrane in the Late Permian through to the Norian.

**Poster**

## What could have been – Implications from laboratory experiments on foraminiferal assemblages for environmental reconstructions

**Anna E. Weinmann[1], Martin R. Langer[1], Susan T. Goldstein[2], Maria V. Triantaphyllou[3]**

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Foraminifera are useful tools in reconstructing aquatic environments. Their biological traits often lead to characteristic faunal assemblages that allow inferences of past or present temperature, salinity, nutrient or oxygen conditions, water depth and others. The study of specific faunal compositions and/or indicator taxa can be applied in biomonitoring as well as paleoecology and –biogeography.

Recent observations have shown that many foraminifera are much more widely distributed than previously thought. This appears in the form of small juveniles (termed "propagules") that are transported into "unnatural" environments but can remain viable even under unfavorable conditions. They remain largely undetected in field studies due to their small size but they can become "visible" in growth experiments under more suitable conditions.

The presence of "exotic" propagules might be one reason behind the often observed adaptive capacities of foraminiferal assemblages, e.g. to temperature, salinity or depth changes. Faunal composition changes often happen very quickly and allow for the high-resolution in environmental reconstructions that make foraminifera useful proxies.

Here we explore the possibilities in potential faunal reactions to different ecological conditions by presenting experimental data from shallow-water lagoons from Corfu (Greece). Though locally sourced, our findings could have implications for other environments as well as paleoecological reconstructions.

# Topics 13: Applied geophysics

## 13a) Rock rheology, deformation transients, and the earthquake cycle

Poster

### Magnetic and structural behaviour of magnetite subjected to cyclic loading under temperature conditions relevant for the upper crust

**Helena Fuchs, Boris Reznik, Frank Schilling, Agnes Kontny**

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Magnetic properties of rocks are used to qualitatively describe the dynamics of tectonic-related deformation phenomena within the Earth's crust. Up to now modifications of magnetic properties are mainly described from static or dynamic shock-related deformations (e.g. Reznik et al. 2016). However, it is generally accepted that tectonic stress accumulates non-uniformly, but remains quite low until a rapid stress variation occurs shortly before and after earthquake propagation or volcano eruption. Rapid stress increase may be especially favorable if an intermediate to high-temperature tectonic loading exhibits a cyclic character. This raises the question whether the magnetic properties of rocks are sensitive to fatigue-assisted deformation under increased temperature.

In order to reveal fundamental changes in magnetite exposed to cyclic loading, samples of a banded magnetite-quartz ore were compared with samples prepared from a natural magnetite single crystal. Cyclic experiments have been carried out using a GABO Eplexor Dynamic Mechanical Analysis (DMA) system allowing controlled force loading with a precision better than 0.1 mN (Klumbach and Schilling, 2013). 40 cycles in 1 K steps from 303 to 623 K have been conducted under a static load of 98 N and a dynamic load of 46 N for about 3 h which corresponds to a maximum pressure of about 10 to 15 MPa. Magnetic properties were studied using the temperature dependence of magnetic susceptibility (induced magnetization). Changes in microstructure were characterized by reflected light microscopy, Raman spectroscopy, X-ray powder diffraction and thermogravimetric analysis.

The most obvious change is a decrease in the sharpness of the Verwey transition of magnetite at 120 K suggesting a decrease of magnetic domain size, and / or a phase transition into hematite via maghemite. The formation of hematite along magnetite grain boundaries on the (001) surface of single crystals is documented by reflected light microscopy. We hypothesize that oxidation and recrystallization in magnetite are two competing deformation mechanisms controlling changes in magnetic behaviour of magnetite. Our study focuses on the question to what extent these competing mechanisms contribute to the magnetic property changes. Therefore, high-resolution transmission electron microscopy is underway to control the deformation of magnetite subjected tocyclic loading.

References

Klumbach, S., and F. R. Schilling (2013), Elastic and anelastic properties of a- and b-quartz single crystals, *Eur. J. Miner.*, (1889).

Reznik, B., A. Kontny, J. Fritz, and U. Gerhards (2016), Shock-induced deformation phenomena in magnetite and their consequences on magnetic properties, *Geochemistry Geophys. Geosystems*, *17*, 1–20.

Poster

### Effect of loading conditions on the nucleation and development of shear zones around material heterogeneities

**Livia Nardini[1], Erik Rybacki[1], Luiz Morales[2], Georg Dresen[1,3]**

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Rock deformation at depths in the Earth's crust is often localized in high temperature shear zones, which occur in the field at different scales and in a variety of lithologies. The presence of material heterogeneities is known to be a cause for shear zone development, but the mechanisms controlling initiation and evolution of localization are not fully understood, as is the effect of loading conditions.

To investigate the effect of boundary conditions on shear zone nucleation, we performed torsion experiments under constant twist rate (CTR) and constant torque (CT) conditions in a Paterson-type deformation apparatus. The sample assemblage consisted of copper-jacketed Carrara marble hollow cylinders containing a thin plate of Solnhofen limestone oriented perpendicular to the cylinder's longitudinal axis. All experiments were run at 900 °C and 400 MPa confining pressure. Under these conditions, samples were plastically deformed and the limestone is about 9 times weaker than the marble, acting as a weak inclusion in a strong matrix. CTR experiments were performed at maximum bulk strain rates of 1.8-1.9*$10^{-4}$ $s^{-1}$, yielding peak shear stresses of 19-20 MPa. CT tests were conducted at shear stresses between 18.4 and 19.8 MPa resulting in bulk shear strain rates of 1-4*$10^{-4}$ $s^{-1}$. Experiments were terminated at maximum bulk shear strains of ≈0.3 and 1.0.

Strain localized within the host marble in front of the inclusion in an area (process zone) where grain size reduction is intense. The local shear strain, estimated from passive markers on the sample surface, is up to 10 times higher than the applied bulk strain at the inclusion tip, rapidly dropping to 2 times higher at larger distance from the inclusion. The evolution of microstructural parameters such as average grain size, shape preferred orientation, aspect ratio and spatial distribution of dynamically recrystallized grains is independent of loading conditions at both investigated bulk strains. Textures within the evolving process zones were determined by electron backscatter diffraction microscopy. Strong preferred crystallographic orientations are observed in the process zone, but no indications are present for the activity of different slip systems at different boundary conditions. Our results suggest that

- material heterogeneities induce stress concentration halos resulting in strain partitioning into localized shear bands
- progressive localization is associated with strain weakening accommodated by dynamic recrystallization and CPO development
- the propagating tip of the shear zone is surrounded by a process zone
- loading conditions do not significantly affect localization during nucleation and transient evolution stages.

Talk

## From Fault Creep to Slow and Fast Earthquakes in Carbonates

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Destructive earthquakes in the Mediterranean and other regions worldwide occur in carbonate terrains. Recent examples are the L'Aquila ($M_w$6.1 2009)and Norcia ($M_w$ 6.5 2016) earthquakes in Central Italy. Surprisingly, within this region, fast (> 1 km/s) and destructive seismic ruptures coexist with slow (< 10 m/s) and non-destructive rupture phenomena. Despite their relevance for seismic hazard studies, the mechanisms controlling the transition from fault creep to slow and fast rupture propagation are still poorly constrained by seismological and laboratory observations. Here, we reproduced in the laboratory the complete spectrum of natural faulting on samples of dolostone representative of the seismogenic layer in the region. The transitions from fault creep to slow ruptures, and from slow to fast ruptures, are caused by simultaneously increasing the confining pressure (P) and temperature (T) up to conditions encountered at 3-5 km depth in the crust (i.e., P = 100 MPa and T = 100 °C). These conditions can explain the observed hypocentral locations of slow earthquake swarms, and the onset of regular seismicity in Central Italy. The transition from slow to fast rupture propagation is due to the increase of ambient temperature with depth, which allows flash weakening to trigger the propagation of fast ruptures that radiate intense high frequency seismic waves.

Talk

## Effect of laboratory high-temperature cyclic loading on magnetic properties and microstructure of magnetite from an iron ore

**Boris Reznik**, **Leo Henrichs, Mario Walter, Frank Schilling**

*Karlsruhe Institute of Technology (KIT), Germany*

In general, it is accepted that during tectonic deformation the applied loading has a static character [1]. On the other hand, tectonic stresses first accumulate non-uniformly, and then increase rapidly causing fault ruptures and earthquakes. Evidently, a rapid stress increase may be especially dominant if the tectonic loading exhibits a cyclic or a fatigue character at elevated temperatures [2]. This assumption raises the question whether magnetic properties of rocks are sensitive to cyclic deformation at elevated temperatures and provide a tool to uncover fatigue behaviour occurring in the crust. In order to verify this hypothesis, samples of a quartz-magnetite banded iron ore were cyclically loaded and subsequently studied by a combination of magnetic and microstructural methods. The cyclic compression experiments, were carried out using an universal testing Instron machine. Modifications in magnetic properties were studied by measuring the anisotropy of low-field magnetic susceptibility (AMS) and the Verwey transition temperature of magnetite. Microstructures were analysed by a combination of reflected light optical microscopy and X-ray powder diffraction while the magnetic domain structure of magnetite was investigated by magnetic force microscopy. In order to separate the effect of cyclic loading from those of temperature and static loading the results obtained for samples subjected to cyclic loading were compared with samples only annealed in vacuum and ambient atmosphere at 500°C as well as for samples only exposed to static compression for several hours at 500°C. The increasing number of high-temperature cycles is correlated with a profound decay of the bulk magnetic susceptibility and the degree of AMS as well as with the appearance of hematite at grain boundaries of magnetite. In the same time, sharp Verwey transitions and well-developed magnetic domains strongly suggest the recrystallization of magnetite. The presented results demonstrate that a fatigue effect of magnetite exists at elevated temperatures. Our first result suggest that the mechanisms behind this phenomenon is a competition between phase transformation and recrystallization, which influences bulk magnetic susceptibility and the degree of AMS.

References

1. Cox, A. & Hart, R. B. 1986. Plate tectonics. How it works. Blackwell Scientific Publications, Oxford. 392 p.
2. Chen, Y-L., Ni, L., Shao, W., Azzam.R. Experimental study on the influence of temperature on the mechanical properties of granite under uni-axial compression and fatigue loading. International Journal of Rock Mechanics & Mining Sciences 56 (2012) 62–66.

Talk

## Deformations and the combined analysis of seismic and GPS weak signals

**Baptiste Rousset[1], William Frank[2], Cecile Lasserre[3], Nikolai M. Shapiro[4], Roland Burgmann[1], Michel Campillo[3]**

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Actual deformations at depth are unambiguously revealed by their geodetic signatures. Unfortunately, the low amplitudes signals for transient deformations of interest are hidden in the GPS position time series by fluctuations of various origins. We present a method to extract weak signals from an array of GPS stations (Rousset et al., 2017). In the same time the earthquake catalogues are used to detect periods of intense activity of low magnitude events that are considered to be indirect signatures of transient deformation, as suggested by the simultaneous observations of strong tremors and slow earthquakes in subduction zones.

We show how the construction of a large catalogue of small events can be used to detect transients in geodetic data with associated surface displacements well below the records fluctuations, and to reveal the intermittent nature of a large Mw7.6 SSE (Frank et al., 2018). When associating advanced array processing for seismic and geodetic data, we are able to quantify slow slip events with Mw<5 in the roots of a continental fault with individual signatures of surface displacements less than 0.1 mm.

Poster

## What controls strain localization of the Alpine Fault, New Zealand?

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The degree of strain localization in fault zones, as expressed in their geometry, is related to the rheological response of the constituent rocks to tectonic loading. This rheological response reflects the interaction of external and internal parameters, which may vary depending on the fault's position in the seismic cycle. External conditions, such as confining pressure and temperature, affect operative deformation mechanisms, and the microstructures that develop. Intrinsic mechanical properties such as compressive strength, Young's modulus and coefficient of internal friction, are controlled by the nature, amount and geochemical composition of the constitutive mineral phases.

Because these relationships between composition, macro- and microstructure, and rheology are well known, field and microstructural observations in combination with mineralogical and geochemical analyses allow investigations of fault zone architectures, their geomechanical behavior, and the time-varying rheological processes generating them.

New Zealand's Alpine Fault is an oblique, dextral strike-slip fault accommodating most of the displacement between the Pacific and the Australian Plates. Exhumation from 35 km depth along a SE-dipping detachment has exposed a 1 km wide damage zone in the hanging wall comprising a brittle core of proto-to-ultracataclasites surrounding the principal slip zone (PSZ), overlain by proto-to-ultramylonites.

Field and laboratory (SEM, XRD and XRF) investigations of surface samples originating from several outcrops along strike of the Alpine Fault, and deeper samples collected during the Deep Fault Drilling Project phase 1A (DFDP-1A) reveal pronounced differences in fault zone architecture expressed as variation in the geometry of the PSZ, which is either a thin (<1cm to < 7cm) layered structure or a relatively thick (10s cm) unit lacking a detectable macroscopic fabric. However, the variations between individual locations on the outcrop-scale are not unambiguously reflected on the microscale as there is no self-similarity in the distribution of layer thicknesses between these scales. Quantities of individual mineral phases do not vary systematically compared to the thickness of the PSZ between the investigated locations, so we infer that the extent of strain localization is not strongly related to differences in mineralogy.

Talk

## Stress history during exhumation from HP-LT metamorphic conditions recorded by microstructures from an extensional shear zone in the Talea Ori, central Crete

**Lina Seybold, Claudia A. Trepmann**

*LMU, Germany*

A major shear zone within high-pressure low-temperature metamorphic sediments in the Talea Ori, central Crete is characterized by extensional shear bands associated with shear band cleavages (C'-type) and discordant quartz veins. The quartz veins show bent elongate grains grown epitactically from the host rock with abundant fluid inclusion trails parallel to the vein wall, indicating vein formation by crack-seal increments during dissolution-precipitation creep of the host rock. The presence of sutured high-angle grain boundaries and subgrains shows that temperatures were sufficiently high for recovery and strain-induced grain boundary migration, i.e. 300–350°C, which is close to the peak metamorphic conditions for central Crete. The generally low amount of strain accumulated by dislocation creep in quartz of the host rock and most veins indicates low bulk stress conditions of a few tens of MPa. The time scale of stress-loading to cause cyclic formation of the discordant quartz veins is on the order of hundred years, estimated from strain rates too high (on the order of 10−10

$s^{-1}$ to $10^{-9}$ $s^{-1}$) in relation to the Maxwell relaxation time of the metasediments undergoing dissolution-precipitation creep. In contrast, some of the young veins discordant to the foliation, but also quartz veins concordant to the foliation and quartz-rich host rocks, can show heterogeneous quartz microstructures with micro-shear zones, sub-basal deformation lamellae and short-wavelength undulatory extinction. These microstructures indicate glide-controlled crystal-plastic deformation (low-temperature plasticity) and associated cracking at transient high stresses of a few hundred MPa with subsequent recovery and strain-induced grain boundary migration at relaxing stresses and temperatures of 300–350°C. The transient, local high stresses are interpreted to be caused by high stress-loading rates controlled by seismic activity in the overlying upper crust. The time scale for stress loading is controlled by the duration of the slip event along a fault, i.e. a few seconds to minutes.

Both, the long-term and short-term deformation recorded by this ductile extensional shear zone are interpreted to represent a relatively early stage during exhumation from peak metamorphic conditions, finally resulting in the updoming and exhumation of the HP-LT metamorphic rocks in the Talea Ori.

# 13b) Geophysics and the new “Standortauswahlgesetz”

**Talk**

## Shallow high-resolution seismic studies of glacial buried structures

**Thomas Burschil, Hermann Buness, David C. Tanner, Helga Wiederhold, Gerald Gabriel**

*Leibniz-Institute for Applied Geophysics, Germany*

Deep structures (>300 m below surface) are foreseen for the German radioactive waste repository according to the Standortauswahlgesetz. The act defines several criteria and minimal requirements for the aspired formation to ensure the long-term safety of the disposal site and the containment. One of those criteria is a depth below the maximum erosional depth of glacial activity during ice ages. Therefore, it is important to understand the evolution of deep glacial erosion structures. Here, we present results of high-resolution seismic reflection studies of Northern Germany and the Alpine realm to image such glacial structures in detail and to derive their evolution.

Modern P-wave seismic reflection with high-frequency vibrator sources and dense acquisition schemes gives a robust, high-resolution insight into shallow structures. The method reveals the shape and infill of buried valleys and overdeepened basins in a high grade of detail. Geological structures like push moraines due to glaciotectonics become visible. S-wave seismic reflection provides often higher resolution and is able to image more details of shallow structures compared to P-waves. But the application of S-wave imaging is more sophisticated and strongly depends on near-surface conditions.

Former projects at the Leibniz Institute for Applied Geophysics focussed on buried valleys in Northern Germany. Within the project CLIWAT, we detect two buried valleys embedded within a glaciotectonic complex of steep-dipping units of kaolin sand and mica clay at the North Sea island Föhr. The valley infill comprises sand and till layers; latter separates two Quaternary and a Tertiary aquifers. A recent project investigates overdeepened basins in the Alpine realm. A net of seismic profiles maps the course of the Tannwald Basin, Baden-Württemberg. The basin incise into Tertiary molasse and is refilled by glacial, fluvial, and lacustrine sediments. Furthermore, a slab of molasse was glacially plucked and deposited at the basin base.

At both sites, P-waves reveal a high grade of details of the geological shape and infill of the basin. S-waves provide an even higher structural resolution than P-waves in particular parts of the profiles. The combination of P-wave and S-wave seismic reflection methods compiles an improved image of the shallow glacial structures. The interpretation of the high-resolved seismic profiles enables us to derive the history of these structures and to estimate future scenarios.

**Talk**

## Thermal characterization of potential nuclear waste repository locations: a multi-disciplinary and multi-scale approach

**Sven Fuchs, Andrea Förster**

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The disposal of radioactive waste is a topic with huge social importance. Understanding the complex geological, geophysical and geochemical conditions is indispensable for the long-term stability and the safe operation of subsurface nuclear waste repositories, regardless whether they are in salt rock, clay or granitoids. In this context, the subsurface temperature controls many natural processes and has mutual effects on the mineralogical and rheological conditions of the host rock and its neighboring rock mass. The characterization of the thermal field and of the governing heat-transfer processes are paramount for the layout of a multi-barrier repository and for its safe operation. Understanding the thermal field depends *inter alia* on the detailed knowledge of the surface heat flow, rock thermal properties (thermal conductivity, thermal diffusivity, heat capacity), and their variation in geological space. The latter requires a geological understanding of facies changes. Moreover, rock thermal properties need to be considered for effective *in-situ* pressure and temperature. In line of these requirements, research at GFZ, in the competence cluster ‘Earth Temperature Field’ is devoted to core-log integration techniques and to mapping and upscaling of data to different geological scale. In addition to indirect approaches to determine rock thermal properties from well-logging data, a particular focus is on laboratory measurements of thermal properties. Thus, a new laboratory vessel was recently tested that was designed and constructed by GFZ as part of the EU-funded ITHERLAB project. With this plethora of methods an overcome of the fundamental lack of data that still is present for all types of the targeted potential host rock types in Germany can be achieved. The data form the basis for the evaluation of both steady-state and transient heat transfer processes targeted on time-dependent solutions of the thermal field for any potential geological location. This is paramount for all scales, but of particular importance for the monitoring and controlling of the near-field temperature which is strongly affected by the technical storage construction and the heat-generating materials contained therein. For the waste-containment area surrounded and protected by clay as backfill material, our lab technology allows to thermally optimize the selected materials (e.g. bentonite mixtures) by studying their thermal behavior under simultaneously varying pressures, temperatures and fluid-saturating conditions.

Talk

## Utilisation of the subsurface for the disposal of high-level radioactive waste

**Michael Kühn, Oliver Heidbach**

*GFZ German Research Centre for Geosciences, Germany*

Society faces a variety of grand challenges impacting the quality of our lives. Disposal of radioactive waste is one of them to be solved within the next decades. After the nuclear meltdown due to the earthquake and tsunami in March 2011 in Fukushima, Japan, the German government decided to step out from nuclear power. Furthermore, it was decided to restart the search for a Deep Geological Repository (DGR) for high-level nuclear waste from scratch.

The criteria of the DGR site selection process are determined in the final report of the "Endlagerkommission" of the German government published in July 2016. This report also defines the schedule which is divided in five stages: (1) site selection, (2) building, (3) storage, (4) closure and (5) monitoring. In particular in the first stage the expertise from geoscientists is required to characterize the subsurface in terms of its structure (e.g. faults, fracture network, lithological layers), rock properties (e.g. strength, permeability, thermal conductivity), field conditions (e.g. stress, temperature, pore pressure) as well as natural and induced themo-hydro-mechanical and biological-chemical processes that change the conditions in the near- and far-field of the DGR. Another key aspect is to predict the changes of the resistance to radionuclide transmission of the three barrier systems (the canister, the backfill between the canister and tunnel, the host rock layer and sealing geological layers above). Since all three potential host rocks have to be investigated in Germany (salt, clay, crystalline) the ultimate goal is to identify the site and host rock type with the highest level of safety.

To address these issues fundamental research is needed to characterize the system and to predict the long-term evolution of the DGR for up to one million years. This research involves further development of e.g. exploration methods of the subsurface to resolve structures on scales of 10-100 m, in situ experiments in underground laboratories, development of predictive modelling tools that investigate the DGR evolution on different spatio-temporal scales, and to engineer dedicated monitoring tools. However, the identification of a suitable site for a repository is not only a technical challenge. Another key aspect is to achieve public acceptance which is a pre-requisite for policymaking in democratic societies. In this paper an overview is given on the current situation in Germany and the geoscientific challenges ahead of us and future generations.

Talk

## Geophysikalische Untersuchungsmethoden für die Standortsuche

**Dirk John Orlowsky, Bodo Lehmann**

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Zur zerstörungsfreien Erkundung möglicher Endlagerstandorte werden üblicherweise Geophysikalische Untersuchungsmethoden eingesetzt. Ihre Bandbreite reicht von Potenzialmethoden (Geoelektrik, Gravimetrie, Elektromagnetik und Magnetik) über die Wellenverfahren wie zum Beispiel der Seismik bis hin zu detaillierten bohrlochgeophysikalischen Untersuchungen. Insbesondere seismische Erkundungsverfahren wie die 3D-Reflexionsseismik sind bei regionalen geologischen Fragestellungen von großer Bedeutung. Für die spezielle Ersterkundung der regionalen Geologie von potentiellen Standorten für „tiefere Endlager" können insbesondere auch verschiedene Verfahren der luftgestützten Geophysik (unter dem Einsatz von Hubschraubern) eingesetzt werden. Für den Einsatz der unterschiedlichen Verfahren müssen generell folgende Grundsätze beachtet werden:

- Je detaillierter das geforderte Ergebnis, um so „näher" sollte man an das Untersuchungsgebiet heran.
- Je höher die geforderte Auflösung der Messtechnik ist, desto größter ist der Messaufwand.
- Der Einsatz von Verfahrenskombinationen der o. g. Untersuchungsmethoden vermindert die „Unsicherheit" bei der Interpretation der Ergebnisse.
- Je komplizierter die Messkonfiguration, umso höher ist der Aufwand bei der Adaption der Messgeräte an die Messumgebung.

Ein geophysikalisches Erkundungsprojekt gliedert sich in die Phasen Planung, Messung, Interpretation und Modellierung. Im Zuge der Planung werden vorhandene geografische, geologisch/hydrogeologische und geophysikalische Informationen ausgewertet, um die Messparameter, Messtechnik und die Geländearbeiten an die jeweils aktuelle Situation vor Ort anzupassen und um den Messablauf zu optimieren. Die in der Messphase gewonnenen Daten werden anschließend ausgewertet (prozessiert) sowie interpretiert und abschließend in ein geologisches 3D-Strukturmodell des Untersuchungsgebietes überführt. Anhand eines solchen Modells ist beispielsweise die Simulation von Wasserbewegungen im tieferen Untergrund möglich. Die neusten wissenschaftlichen Entwicklungen lassen dabei auch die Simulationen mehrerer Phasen zu.

Neben den oberflächengestützten Verfahren werden geophysikalische Untersuchungsmethoden (zum Beispiel Seismik und Radar) auch in Bohrlöchern sowie Untertage eingesetzt, um den Untergrund detaillierter zu erkunden. Als Beispiel wird die Erkundung des inneren Aufbaus eines Salzstocks mit Hilfe eines richtungssensitiven 3D-Bohrlochradars genannt. Allerdings muss für hochauflösende Untersuchungen eine Bohrung in den möglichen Endlagerbereich abgeteuft werden, so dass dieser in gewisser Weise bereits „beeinträchtigt" wird. Mit dem 3D-Bohrlochradar können Störungen oder Heterogenitäten in massiven Festgesteinen wie Salz oder Granit in bis zu einige 100 Meter Entfernung von der Bohrung erfasst werden.

Zusammenfassend ist zu erwähnen, dass für geophysikalische Untersuchungen an möglichen Endlagerstandorten immer eine der Fragestellung und den Standortgegebenheiten angepasste Methodenkombination notwendig ist und individuelle Erkundungskonzepte erforderlich sind. Wichtig ist die interdisziplinäre Zusammenarbeit von Geologen, Geophysikern, Geodäten etc.. Zudem besteht Forschungsbedarf hinsichtlich der Weiterentwicklung der Messtechnik sowie der Auswerte- und Interpretationstechniken.

**Poster**

## The SpannEnD project – crustal stress data, stress modelling and modelling tools for the site selection process of a deep geological repository of radioactive waste in Germany

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The assessment of the geomechanical stability of an underground facility is a challenging task in particular for a deep geological repository for high-level radioactive waste, where long-term stability for one million years is requested. The rock will undergo stress changes due to endogenic and exogenic processes, which will affect the overburden and horizontal stresses likewise. To assess if these stress changes will evolve into a critical stress state, knowledge of the contemporary in-situ stress and potential future stress changes are a pre-requisite during the site selection process.

Several methods are used as stress indicators, that provide information on the orientation, regime and magnitude of stress in the crust. However, these data are sparse, un-evenly distributed and incomplete as they do not provide all six independent components of the stress tensor. Interpolation or extrapolation of such data is quite common, but discontinuities and inhomogeneities have a strong impact on the orientation and magnitude of stresses. Geomechanical-numerical modelling allows representing these features to estimate the full stress tensor continuously in the 3-D space. These physics-based stress predictions facilitate detailed insight into the present day stress state plus potential future changes that may be expected within the next million years such as tectonic shortening, ice ages or mass redistributions which could lead to failure.

SpannEnD stands as an acronym for “Spannungsfeld Endlager Deutschland” and is a recently started collaborative research project of three German research institutions, funded by the BMWi. It aims to set-up a geomechanical numerical model for the continuous prediction of the 3-D stress tensor in Germany. Independent from future host rock decisions, the model will be focused on the basement structures and the sedimentary basins altogether. The all-German model has the advantage, to take large-scale geological structures as well as first and second order stress sources into account. Such a geomechanical-numerical model has to be calibrated on in-situ stress data to come up with meaningful boundary conditions. Therefore, the project will be the starting point for a comprehensive database for the available contemporary stress magnitude data. To take different measures of quality between the methods into account, a quality ranking system shall be part of the development. Furthermore, geomechanical numerical modelling tools will be further developed, e.g. to allow a fast and automated calibration process as well as the derivation of boundary conditions from regional models for local site models, which will be essential during the site selection process.

**Talk**

## How Deep is Deep Enough for a Safe Repository?

**Frank R. Schilling**, **Birgit I.R. Müller**

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It is astonishing that for mine repositories minimum depths of 150-500 m are foreseen (“Standortauswahlgesetz” [StandAG]), whereas for deep wells more than 3000 m are discussed.

The actual goal for a high grade nuclear waste repository in Germany may be summarized according to “StandAG” :

- Depth of at least 150 m, better > 500 m should be used for a mined repository
- The repository needs to be qualified for at least one Million years (“Nachweiszeitraum”)
- The host rock should guarantee an effective containment zone (“Einschlusswirksamer Gebirgsbereich”)– even after one Million years.

From a geological perspective, the minimum depth requirement needs to adress at least the following boundary conditions:

- around ten massive glaciations, if we look for the one Million years, set as perspective for repositories.
- “standard engineering” uses safety factors of two for dangereous issues.

Depending on where we want to put our disposal site, the effect of glaciations may vary significantly. Here we discuss, a virtual repository site within the North German Basin. The approach can be used for other sites as well.

1. Bending of the crust:
   In the past, the bending potential of glaciation for the whole crust, especially at the ice-bulge front, has not been in the focus of Germans researcher. Therefore, most models look at glaciation effects only in the uppermost few hundred meters of the crust. However, as shown in Bracke *et al.* (2016) (Tiefe Bohrlöcher, Bericht Kommission Lagerung hoch radioaktiver Abfallstoffe

K-MAT 52), the bending of the Earth`s crust will lead to a massive modification of the stress field. During a massive glaciation, failure even down to > 1 000 m need to be taken into account. There are independent geological observations which confirm these models.

2. Glacial Channels
   In front of the ice bulge, a huge amount of water has to be transported away. This has formed > 350 m deep Channels in the younger past in northern Germany. This may destroy a significant portion of the effective containment zone. Especially, if we take into account, that such channels can lead to additional local stress amplification.

If one adds the 350 m deep channels to the required > 1 000 m depth to avoid failure due to bending, than one ends up with a minimum depth of 1500 m, even if a rather small safety margin is applied – independent if on prefers to use a mine or a deep wet shaft (well).

**Talk**

## In-situ rock characterization with Mini-Seismic Methods in underground facilities

**Kristof Marian Schuster**

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For a comprehensive in-situ rock characterization in underground facilities BGR developed different ultrasonic and seismic methods, which we call Mini-Seismic Methods (MSM). Underground facilities are used for testing and understanding of processes which are relevant for safe storage of radioactive and toxic waste. From an actual German perspective potential host rocks which are of interest for establishing final repositories are argillaceous rocks, rock salt and crystalline rock.

MSM are quick employable, robust and relatively cheap tools which allow a reliable access to relevant basic geomechanical rock properties. MSM were performed in all potential host rocks with different objectives, starting from an initial local site characterization until monitoring the evolution of Excavation Damaged / disturbed Zone (EDZ/EdZ) features (creation and sealingof EDZ). Methods are applied in single boreholes, between two or more boreholes, along or between drifts and as a combination of borehole and drift based methods. Piezoelectric transducers are used as receivers. As ultrasonic or seismic sources piezoelectric actuators and different impact tools are used. Data are recorded with transient recorders with up to 160 channels and up to 25 MS/s and dynamic ranges of 24 bit.

Exemplarily, results gained in different potential host rocks for radioactive waste disposal with multipurpose emphasis can be presented. Beside important seismic parameters several dynamic elastic parameters are derived. The interpretation allows statements about geomechanically induced features, e. g. detection of cracks, fractures and anomalies, characterization and distinction between EDZ and EdZ features, Borehole disturbed Zone (BdZ) features and illustration of lithological and stratigraphic features.

Furthermore, high resolution borehole based MSM are currently used to contribute to the understanding of “reconciling static and dynamic elastic properties” in Opalinus Clay. Concerning the derivation of several dynamic elastic parameters, like for example Young’s modulus, in-situ MSM provide several advantages compared with laboratory tests.

The following example from MSM in the Mont Terri rock laboratory, Switzerland, shows the high spatial resolution of derived seismic velocities. A 70 m long borehole was used for a predictive tunnel site investigation.

**Fig. 1:** Apparent $v_p$ distribution (running average over 3 points) derived from ultrasonic borehole measurements in steps of 5 cm at the Mont Terri rock laboratory (Opalinus Clay). Indicated “anomalies” correlate well with features in core mapping data.

# Topics 14: 3D applications in the geosciences

## 14a) Computational geosciences

Poster

### Project TUNB – An overview of recent R&D work in the German North Sea sector

**Frithjof Bense**[1], **Fabian Jähne-Klingberg**[1], **Heidrun Stück**[1], **Simon Müller**[1], **Jashar Arfai**[1], **Marco Wolf**[1], **Astrid Wobbe**[2], **Stephan Steuer**[1]

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Within the project „Subsurface potentials for storage and economic use in the North German Basin" (German acronym TUNB), the Federal Institute for Geosciences and Natural Resources (BGR) and the geological surveys of the northern German federal states are developing a 3D model of the North German Basin. Embedded in the project, fundamental and applied R&D work is conducted by the BGR in the German North Sea.

In more detail, the following applied topics are covered:

- detailed seismic mapping and seismic stratigraphic analysis of Late Paleozoic to Tertiary sedimentary successions
- seismic mapping of amplitude anomalies in relation to shallow gas
- seismic mapping of source rocks in the outer NW German North Sea sector (Entenschnabel)
- development of a 3D basin and petroleum system model for the NW German North Sea
- spatial distribution and variation in the structural style of Tertiary polygonal fault systems, Quaternary tunnel valleys, and crestal faults of salt-structures, their spatial superposition, structural linkage and possible impacts on barrier rock integrity
- assessment of $CO_2$ storage potentials in the NW German North Sea

The focus of the fundamental research topics is twofold: first to obtain a more comprehensive and detailed picture of the deeper subsurface and, secondly, to get a thorough understanding of individual structural features in their geodynamic context. The fundamental research topics introduced here include:

- timing, spatial distribution and mechanisms of halotectonic deformation of Late Rotliegend sedimentary successions
- detailed seismic mapping and analysis of faults and salt-structures
- spatial distribution and evolution of erosional valleys along the 'Late Cimmerian Unconformity' and its possible causes
- structural style, timing, kinematics and subsidence history of Mesozoic rift-raft structures (e.g. southern Central Graben, Horn Graben)
- interpretation and structural restoration/balancing of halotectonic effects, Mesozoic rifts as well as their Paleozoic pre-cursors
- subsidence analysis in the outer NW German North Sea sector (Entenschnabel)
- techniques for the visualisation of structural uncertainties in 3D models
- cross-border harmonisation of seismic interpretation data, stratigraphic definitions and 3D models

Poster

### A seismic interpreter's perspective on geological uncertainty – examples from the assessment of $CO_2$ geological storage prospectivity

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Prospectivity of $CO_2$ geological storage is – according to IPCC (2005) – a qualitative assessment of the likelihood that a suitable storage location is present in a given area, based on available geological information. Consequently, any assessment of $CO_2$ storage prospectivity requires inter alia a detailed knowledge on the distribution of appropriate reservoir rocks (rocks with high porosity and permeability; i.e. sandstones) and barrier rocks (rocks with low porosity and/or permeability, providing a barrier to the migration of fluids out of the reservoir rock; i.e. clay and salt rocks). In offshore areas, such information is generally derived from geological and geophysical data, i.e. deep wells and reflection seismic data.

We will illustrate and discuss factors of uncertainty which are inevitably linked to the interpretation of geological and geophysical data. For example, as the distribution and quality of geological and geophysical data may be heterogeneous throughout a study region, information may be inadequate to fully constrain a geological in-depth interpretation locally. In this case the characterization of the reservoir-barrier-rock units rely on extrapolation of geological data from adjacent regions based on conceptual ideas (i.e. a heuristic 'rule of thumb' approach) and is thus subject to a certain degree of uncertainty.

Factors addressed here include: (i) handling of under-determined regions or regions without well-control (no or only few data available), (ii) limited knowledge on tectonics and the sedimentary environment, (iii) interpreters bias, (iv) seismic picking errors, (v) errors in thickness and depth estimations based on time-depth conversion (seismic velocity modelling).

Using examples from previous assessment studies in der German North Sea (Jähne-Klingberg et al. 2014, Bense et al. 2017), we provide a "picture book" to illustrate typical pitfalls in geological interpretation and subsequent storage prospectivity assessment based on above mentioned parameters. Additionally we suggest techniques to illustrate and communicate geological uncertainties in a straightforward way.

References

Bense FA, Jähne-Klingberg F (2017) Storage potentials in the deeper subsurface of the Central German North Sea. Energy Procedia 114, 4595-4622.

Jähne-Klingberg F, Wolf M, Steuer S, Bense F, Kaufmann D, Weitkamp A (2014) Speicherpotenziale im zentralen deutschen Nordsee-Sektor. Report, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.

**Talk**

## Spatial reconstruction of the Burdigalian (early Miocene) depositional history in Bavaria (eastern North Alpine Foreland Basin)

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The North Alpine Foreland Basin is an orogenic basin situated mainly in southern Germany, extending to Switzerland in the East and to the Czech Republic in the West. It served as the depositional environment for various facies of the Molasse sea, consequently one of the largest Miocene sedimentary archives arose. This epicontinental sea belonged to the Paratethys ocean with temporarily open seaways. The paleogeography was mainly influenced by tectonics and sea level fluctuations. In the early Burdigalian (18-20 Ma) a transgressive phase caused the deposition of several marine formations, the so called Upper Marine Molasse. During the subsequent regressive phase, successively the formations of Upper Brackish Molasse and Upper Freshwater Molasse deposited. Because of different on- and offsets of the seaways in the eastern and western part of the North Alpine Foreland Basin, these formations are not uniform throughout the entire North Alpine Foreland Basin.

Especially the depositional history and paleogeography of the eastern North Alpine Foreland Basin are poorly understood. The accepted lithostratigraphic model suggests that the present formations are deposited in superposition and as chronostratigraphic distinct sequences. However, current research proposes that several formations existed contemporaneously. The objective of this study is to improve the lithostratigraphic model of the Molasse formations. By doing a three dimensional reconstruction of all Burdigalian formations in the eastern North Alpine Foreland Basin, the interactions of certain formations will be more understandable. The question, if formations persisted throughout their current stratigraphic age, will be answered.

The spatial model is based on borehole data of 108 drilling sites, evenly distributed across southeastern Bavaria. The reconstruction will be performed with "QGIS" and presumably with "Petrel" and later interpreted with additional information on the tectonic deformation. Preliminary results revealed spatially interlocking formations in the eastern North Alpine Foreland Basin, which is showing a higher age plasticity of present formations than previously assumed. The expected outcomes of the 3D reconstruction will contribute to the understanding of the regional lithostratigraphy and should help to improve the biostratigraphic concept in the Molasse basin.

**Poster**

## OpenGEO – an application for geological 3D modelling

**Ralf Kloke[1], Christian Dresbach[1], Detlef Schlüter[2]**

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openGEO is a program for 3D modeling of complex geological structures developed by consultant Detlef Schlüter. It is used among others by the Federal Institute for Geosciences and Natural Resources for research projects as well as in running projects in the field of nuclear waste repositories.

openGEO uses relational data bases for data storage and utilizes a CAD software for data visualization. This approach allows a combination of graphic/engineering design capabilities of a CAD software with query and search capabilities of a database engine. External data are being integrated completely and unaltered, including all available metadata, while each modification is stored in a version history. This applies to borehole data as well as geophysical data, e.g. from seismic, geo-electric, helicopter electromagnetic surveys. openGEO especially supports the visualization and interpretation of underground geophysical surveys, for example ground penetrating radar that need to be analyzed in three dimensions.

Especially the full compatibility to all drawings created with the CAD-software is a valuable advantage. Thus, openGEO offers the possibility to directly integrate mine surveying documents like mine layout plans and mine workings for further use. An additional usage is the combination of Building Information Models (BIM) with geological 3D models. The CAD software offers full interoperability with other geological modelling programs as well as 2D and 3D GIS Systems. The geological models created with openGEO form the basis of different kinds of numerical modeling.

As opposed to modeling software working on the basis of interpolation, openGEO horizon creation relies on lines instead of points. In this way the processing user directly steers the horizon definition, since openGEO does not generate new data points off the construction lines. If, for example, contour lines are being used for model generation the creation process is similar to the editing of a stripped geological map. The models created with openGEO are hollow bodies that share one single boundary surface at their contact. These bounding surfaces are so called two-sided surface in which two structural units are assigned to each line of the surface. An accidental mix up of structural units is thus precluded.

The Federal Institute for Geosciences and Natural Resources utilizes openGEO in repository projects incorporating the complex internal setting as well as horizons of the cap rock, the overburden and the adjoining rock formations of salt structures and other geological settings in Northern Germany.

**Talk**

## Transfer of geological 3D models into numerical models

**Tatjana Thiemeyer (née Kühnlenz)**[1], **Herbert Kunz**[1], **Jörg Hammer**[1], **Sandra Fahland**[1], **Matthias Beushausen**[1], **Detlef Schlüter**[2]

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Geological 3D modeling is crucial for the understanding of geological development of structures or regions and for planning of exploration works. Moreover, 3D models will be increasingly used as a basis for calculations of THM processes due to the exploitation of the underground (geothermal energy, mining, cavern sites, underground disposal and repositories) regarding the simulation of the present status as well as a prediction of barrier integrity for perspective usage. For purpose of numerical calculations a geological 3D model has to be transferred into a finite element (FE) model. Adapting to the shape of a complex geological body the tetrahedral element type is favorable. To generate the tetrahedral grid for a geological body, the 3D surfaces representing the boundaries of geological units must have a harmonic triangle net free from defects (none intersection, none zero-area faces, watertight). In order to create and to check a harmonic triangle net structure as well as to generate a tetrahedral grid for numerical simulations from a 3D geological model, BGR developed a special workflow which is processed in the in-house application GINA_OGS. GINA is able to recognize and eliminate defects in a triangle net before generating the tetrahedral grid model as a basis for robust THM simulations. For tasting the transferability of geological 3D models into THM models, two types of geological structures were considered: tectonically overturned salt structures and flat bedded salt formations. Thus, two different transfer workflows were applied. Both workflows are applicable for generating harmonic triangle nets for 3D models which represent the basis for generating FE models for THM simulations.

During numerical simulations of THM processes near a mine, the geological conditions in combination with the mine geometry must be considered. Technical elements, like boreholes, tunnels and shafts, which are intersecting the geological structure, have an influence on the results of numerical calculations. Therefore they must be integrated into the geological 3D model. A special workflow for their integration into the numerical model and following creation of FE model was also developed in this study. The results of the numerical calculations, based on comprehensive geological-geotechnical FE models, enable an evaluation of the integrity of geological barriers as well as for a long term safety analysis.

**Talk**

## State of the art 2D-3D geospatial methods for surface modelling and characterisation in the geosciences

**Tobias Kurz**[1], **Simon Buckley**[1,2], **Nicole Naumann**[1], **Kari Ringdal**[1], **Benjamin Dolva**[1]

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Geoscience is a broad discipline that is currently benefitting from developments in geomatics acquisition, processing and data exploitation methods made over the last decades. Acquiring and working with 2D–3D image data has been never so accessible and is seeing a continued increase in user-friendliness. This results in numerous new and novel applications in many areas, at different scales, and across academia, industry, private and public sector.

This contribution reviews novel 2D–3D geospatial methods for geological outcrop characterisation, and demonstrates various applications with case studies. Today, conventional fieldwork is commonly complemented with 2D and 3D digital mapping methods. Outcrop studies were revolutionised by establishing terrestrial laser scanning (TLS), often combined with high-resolution photographs to generate photorealistic 3D outcrop models. Representing outcrops as digital 3D models addresses the 3D aspect in geology and provides new opportunities for numerical and statistical exploitation of outcrops. With advances in computer vision, Structure from Motion (SfM) has become a cost efficient and user-friendly method for 3D imaging without the requirements of sophisticated and costly hardware. Today drone technology extends dramatically the opportunities and applications for small to medium scale 2D–3D imaging.

New imaging sensor such as multispectral, hyperspectral and thermal cameras or terrestrial interferometric synthetic radar (InSAR) are developing rapidly and adding new information to outcrop studies. Spectral imaging allows the extraction of mineral and lithology information and can therefore complement 3D geometric data with valuable material information. Spectral sensor technology becomes increasingly miniaturised, resulting in more flexibility for field usage, as well as particularly for drone applications in outcrop studies. Recently, hyperspectral imaging has become more accessible for geoscience applications. Various types of cameras are available today and devices and specifications can be chosen according to application requirements, such as spectral ranges (visible, near, shortwave and thermal infrared) or image acquisition mode such as pushbroom sensors or frame cameras. Case studies from carbonate and coal mining as well from subsurface tunnel faces demonstrate 3D outcrop studies integrated with close range hyperspectral imaging.

Due to the trend toward multi-sensor studies, image and data integration, as well as the co-visualisation of different data types, has been become an important aspect in geosciences. Automatic workflows are increasingly simplifying the co-registration of image data. 3D outcrop models can be used as a framework to integrate and co-visualise different image and data types, ultimately supporting integrative data exploitation and interpretation. Examples of a novel co-visualisation solution will be shown as implemented in the in-house LIME software.

Talk

## Application of 3D outcrop data in reservoir geology on the examples of fractured carbonates in the Upper Rhine Graben

**Lena Merz, Uwe Baier, Christoph Hilgers**

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3D field applications have a high potential to gain large amounts of data in a relatively fast time from former inaccessible reservoir analog outcrops. We apply terrestrial laser scanning (t-LiDAR) and UAV-based Structure from Motion (SfM) on fractured Muschelkalk outcrops on the graben shoulder of the Upper Rhine Graben. Upper Muschelkalk carbonates are an important E&P target in the Upper Rhine Graben, but reservoir characterization from 1D subsurface data is insufficient for a broad understanding of fracture networks in the tight carbonates. Therefore, we work in well exposed open pit mines with the aim to unravel fracture spacing, orientation and history and help improve reservoir exploration and production.

Our terrestrial laser scanner (Lidar) derives the fracture orientation and spacing from steep inaccessible vertical quarry walls with an in-house developed workflow. Additionally, quarry floors can be imaged by our UAVs, resulting in high resolution orthophotos from which we derive relative age relationships and lateral continuity of fractures. Based on quarry data, we build a discrete static 3D fracture network and are able to simulate fluid flow with state of the art software tools such as FracMan, FracaFlow and Petrel.

The Upper Muschelkalk in the studied outcrop reveals m-scale kink-bands and buckling in highly anisotropic layers of carbonates and shales revealing the tectonic history of the area generally driven by the alpine stress field and more recent evolution of the Upper Rhine Graben.

A minimum of five fracture generations were derived from quarry wall- and floor data. Based on abutting relationships, the oldest and most persistent fractures strike N-S. However, N-S striking fractures, which are often carbonate cemented, abutting on WNW- ESE striking fractures can also be observed pointing to fracture reactivation. We measured open fractures across steep faults but were not able to establish fault related fracture corridors, but cemented carbonate veins.

First results show that our automated fracture detection workflow based on point cloud data in combination with field observations are a promising tool for reservoir scale outcrop characterization. We suggest that the fractured carbonates in the Rhine graben region show a different structural history than originally thought.

Talk

## 3D models of internal structures in Rotliegend-Zechstein salt structures in the Glückstadt Graben, Northern Germany

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Permian (Upper Rotliegend to Zechstein) evaporitic rocks built up salt structures in the central part of the Southern Permian Basin. Onshore in the Glückstadt Graben, Rotliegend-Zechstein salt structures occur as salt walls and salt diapirs. In the ongoing project InSpEE-DS, the internal structures, composition and genesis of the Rotliegend-Zechstein salt structures are investigated to gain a better expectation of the potential storage capacity for hydrogen and compressed air energy (CAES). 3D models serve as an analysis tool and should include all accessible information. 3D-modelling is performed by the software openGEO with a graphic AutoCAD core.

Data of more than 500 boreholes, 1:100,000 cross sections of the Geotectonic Atlas (GTA) and 3D underground models of Schleswig-Holstein and Hamburg (StörTief) and North Lower Saxony (TUNB project) were accessible for this study. Core descriptions and logging data of all boreholes were checked and adjusted to actual Zechstein stratigraphy. GTA cross sections were digitized and georeferenced. Due to the heterogeneous data density, the salt wall Heide was chosen as a case example for modelling the internal Rotliegend-Zechstein structures. The 3D shape of Heide salt wall originally modelled with GOCAD, was modified with openGEO to mount all 356 boreholes near or in this salt wall. Based on the implemented 3D underground models and boreholes, new cross sections were created. With horizontal profiles of the 3D space including cross sections and boreholes, the line framework of the Rotliegend-Zechstein transition was created and triangulated to a 3D plane.

The 3D model of Heide showed that in general, the stratigraphic underlying Rotliegend succession is located in the centre of the salt wall while the Zechstein succession at the rim. The Rotliegend-Zechstein transition is close to vertically oriented in the southern part of the Heide salt wall, whereas the transition in the northern part is overturned with a low-angle inclination and an overlying Rotliegend thickness of up to 600 m. The transition from Rotliegend to Zechstein in the Heide salt wall is typically built up of impure rock salt and red siltstones of the Upper Rotliegend succession to dolomites and anhydrites of the Werra (z1) and Staßfurt formation (z2) followed by Staßfurt rock salt of the Zechstein succession.

With 3D-modelling it is possible to map the internal structure and assess the occurrence of rigid layers inside the salt structure, which helps to predict constraints for potential energy storage in Rotliegend-Zechstein salt structures that are less investigated so far.

**Talk**

## 3D modelling of the effect of thermal-elastic stress on grain-boundary opening in quartz grain aggregates

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Grain and phase boundaries are one of the most important features of crystalline materials. They affect physical properties of rocks, such as rheology, strength, resistance to cracking and corrosion, and fluid permeability and provide information on their tectonometamorphic history.

Based on focused ion beam (FIB) sample preparation, transmission electron microscopy (TEM) of quartz grain aggregates from metamorphic rocks shows that many grain boundaries are partly or totally open on the nanometre scale [1]. This is also true for grain and phase boundaries of other rock-forming minerals in metamorphic as well as magmatic rocks [2]. The probable explanation for this observation is that grain-scale thermal-elastic internal stresses induced by exhumation, i.e. cooling and decompression overcome the strength of grain and phase boundaries. Internal stresses form during temperature- and pressure changes because the related thermal and elastic material properties exhibit differences between phases (thermal-elastic mismatch) and are generally anisotropic (thermal-elastic anisotropy). Moreover, grain shape has a major impact on the internal stress field. Stresses are amplified geometrically at corners and sharp edges of grains. Therefore, an accurate assessment of how and when grain boundaries likely open during exhumation requires that thermal elastic mismatch and anisotropy as well as the specific 3D rock microstructure are considered. Here, we simulate the cracking of quartz grain boundaries during the exhumation of quartzite at the grain scale with 3D numerical forward modelling [3]. We combine contact mechanics with the finite-element method. Model grains exhibit an anisotropic, linear elastic rheology with an anisotropic thermal-expansion tensor. Grain boundaries are modelled as contact surfaces with a non-linear strain softening rheology in tension and a Mohr-Coulomb rheology in shear. Grain-boundary fracture evolution during the exhumation along geologically relevant P-T paths and compare the results with statistical properties of cracked quartz grain boundaries in real quartzites. Implications for the physical properties of quartz grain aggregates will be discussed.

**Poster**

## 3D Modeling of Geothermal Reservoirs in Mesozoic Delta Systems of the North German Basin – First Approaches

**Jasmaria Wojatschke, Gregor Barth, Karsten Obst**

*Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern, Germany*

The North German Basin (NGB) as part of the Central European Basin System contains up to 3500 m thick successions of Triassic and Jurassic sediments. These sediments were mainly deposited by fluvial to deltaic processes influenced by cyclic transgressions and regressions according to regional changes of the sea level. Sandstone dominated facies is recorded for the Early Triassic (Middle Buntsandstein), the Middle and Late Triassic (Carnian and Rheatian) as well as for the Early and Middle Jurassic. These sandstone bearing lithological units are in the focus for geothermal use, which is proved to be possible since the first geothermal heating plant started its operation in NE Germany in 1984.

To establish new geothermal projects and to guarantee successful drillings, tools are necessary that allow a profound prediction of high quality reservoirs with good porosities and permeabilities. Modern lithostratigraphic investigations and facies analyses on basis of nearly completely cored mapping wells and several hundreds of oil and gas exploration wells with geophysical wire logs resulted in the development of detailed facies maps showing the distribution of clastic sediments according to their position in different parts of deltaic systems (e.g. Wolfgramm et al. 2014, Zimmermann et al. 2018). Especially sands of the distributary mouth-bar deposits are in the focus for geothermal uses. The visualization of complex distributary channel patterns in 3D will help decision makers in politics and economy in planning and establishing new geothermal projects.

First approaches of 3D geothermal reservoir modelling can be shown and discussed for the Toarcian deltaic system. Based on more than 400 wells drilled in NE Germany, the position of marker horizons, e.g. the base and top of the reservoir, and the proportion of different facies was determined. This information is used to create a 3D model, which combines the original facies distribution with the recent geological position. To display correct depth and morphology of potential target areas, secondary modifications by erosion, salt movements and fault tectonics have to be considered. Having a volumetric model, reservoir parameters can be implemented for further calculations, e.g. to evaluate hydraulic conditions and production rates.

**References**

Wolfgramm, M., Franz, M., Agemar T. (2014) Explorationsstrategie tiefer geothermischer Ressourcen am Beispiel des Norddeutschen Beckens in *Bauer, M. et al., Handbuch Tiefe Geothermie*, 463–505.

Zimmermann, J., Franz, M., Schaller, A., Wolfgramm, M. (2018) The Toarcian-Bajocian deltaic system in the North German Basin: Subsurface mapping of ancient deltas-morphology, evolution and controls, *Sedimentology*, **65**, 897–930.

**Talk**

## Salt structure modelling in the central German North Sea: An approach to geological consistent 3D models

**Marco Wolf, Heidrun Louise Stück, Fabian Jähne-Klingberg**

*Federal Institute for Geosciences and Natural Resources, Germany*

Within the project TUNB (Subsurface Potentials for Storage and Economic Use in the North German Basin) of the Federal Institute for Geosciences and Natural Resources (BGR) a 3D structural model for the German North Sea sector will be created, including thirteen stratigraphic horizons (from base Zechstein to base Rupelium), major faults and salt structures. The latter show as long elongated salt walls a length of up to 100 km and change their shape several times from one end to the other due to differences in the kinematics and subsidence history.

The approach to a suitable geological 3D-model of these complex salt structures starts with a reliable, geological consistent interpretation of 2D-seismic data, dealing also with data heterogeneity in terms of spatial distribution and quality (processing etc.). The complexity of the salt structures has a huge impact on the modelling process in Paradigm SKUA/GOCAD. Based on this fact we needed to develop an approach for a consistent 3D-modelling workflow in Paradigm SKUA/GOCAD. With this contribution we want to show our hitherto existing results from salt structure modelling in the central German North Sea and we will present our threefold working concept on salt structure modelling from 1) seismic interpretation and it`s re-evaluation regarding geological consistency, 2) preparation for 3D-modelling and 3) actual modelling methods in Paradigm SKUA/GOCAD. Furthermore we will address workflows to evaluate accuracy and visualise uncertainties of this process.

Additionally we will highlight elected implications of our modelling concept on the geological results. In the end we will compare our results to former 3D-models in our study area.

# Topic 15: Outreach, education, and the societal relevance of Geosciences

## 15a) Geoscientific collections in the area of responsibility between science and public relations

Talk

### The development of Chinese fossil related industry and the cooperation with Germany

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Geoscience, with its importance for popular science education, has attracted increasing public focus. Because of the unique ornamental value and educational function of fossils, palaeontology has become the key for the development of geoscience. Our team, NAQIYI fossil studio, aims to promote the Chinese fossil community and to encourage the international exchange between global fossil communities. Particularly in recent years, we have had close cooperation with the German fossil community and made considerable achievements, which can be reflected in four main aspects.

(1) Fossil product innovation

Functional decorative products such as lamps and cups inspired by fossil morphological characters and applied to the market have already received positive feedback.

(2) Portable device application

Mobile App based on virtual reality (VR) and 3D image technology was designed, which will improve and enhance the experience of museum visitors.

(3) Fossil tour

With the increase of knowledge, fans of Chinese fossils will not only be limited to the Chinese fossil deposits. The famous European fossil deposits, e.g. Solnhofen, Messel, are great attractions. We made the first attempts to organize European fossil tours with German colleagues last year. It proved to be a valuable experience.

(4) Fossil collection exchange

Diversity of fossils in various deposits differs greatly. Therefore, an exchange system will truly benefit museums and the public in parallel. For independent organisations, we have established mutually beneficial collection exchange relationships; however, cooperation at the official museum level between Germany and China still requires effort.

Compared to the German fossil industry, the Chinese fossil industry is young and has vulnerable points. Nonetheless, an advantage of the Chinese is artistic design of products and promotion and marketing. We hope that our experience will encourage future mutual efforts to inspire the German geoscience sector and related fields. We are confident about future cooperation prospects between German and other European colleagues.

Poster

### LithoLex – relaunched

**André Bornemann**[1], **Martin Hiß**[2,3], **Franz Plattetschläger**[1]

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The lithological lexicon “LithoLex” (https:/www.bgr.bund.de/Litholex) is a dynamic database that comprises all defined lithostratigraphic units of Germany and makes them accessible to the public via a web interface. LithoLex is a joint-venture of the German Stratigraphic Commission (DSK) and the Federal Institute of Geosciences and Natural Resources (BGR). The DSK and its subcommissions are providing the content, i.e. definitions and descriptions of the lithostratigraphic units, whereas the BGR is in charge of maintaining the database and providing these geoinformation to the public. LithoLex is a very popular application and heavily used by the geoscientific community as indicated by access rates of more than 20 000 per month on average over the last 10 years.

The first version of LithoLex went online on the 07th August 2006 starting with only 80 data sets from the Cretaceous and the Cenozoic. Today (May 2018) the database comprises 777 entries from the Proterozoic until the Quaternary. It is planned that the database will cover all 1290 units currently considered in the "Stratigraphic Chart of Germany 2016" (STD2016) at some point in the future.

Since LithoLex has been developed more than 10 years ago, the IT architecture of the current version is far from being state-of-the-art, accordingly a re-programming of the database backbone as well as the web interface became necessary. During the first half of 2018 LithoLex has been newly programmed and the relaunch is scheduled for the end of July. The new version will not only provide a fresh look of the application, but also a couple of new features such as the implementation of a semi-automated workflow for the stratigraphic subcommissions allowing them to edit old entries and to add new ones more easily.

**Talk**

## OutcropWizard - The mobile outcrop database

**Edouard Grigowski, Martin Monschau, Gösta Hoffmann**

*University of Bonn, Germany*

Digital media have become more prevalent in both universities and society, in general, in recent years. They fill a critical gap between traditional media theory and practice using in teaching nowadays. E-learning tools can close this gap through scalability and mobility, thus supporting theoretical classes with digital media, and practical classes with theoretical background data. This is true especially for geoscientific education, where the content has spatial relevance. With this in mind we developed the Android e-learning application, OutcropWizard, which serves as a virtual excursion guide. OutcropWizard displays outcrops and points of geoscientific interest as markers on a map and provides detailed information on stratigraphy and lithology as well as outcrop description. Students and interested users can use OutcropWizard to search for, learn about and locate outcrops, share their impressions via pictures and comments, and discuss topics among themselves within the app. More enthusiastic users can even upload their own outcrops and contribute to the project, thus supporting the app by increasing the user based content. Students can experience the geology of an outcrop in the classroom, with the help of 3D-models and videos, before visiting said outcrop. OutcropWizard also allows students, professionals and interested users to explore Earth's history in their own surroundings. The upcoming implementation of our virtual professor will facilitate e-learning in the geosciences even more. Other advantages of the app when compared to classical approaches such as books and information boards are: the information is easily updatable; the content is interactive, the content can be made available for all languages and is accessible for people with physical handicaps. Finally, OutcropWizard is also an inexpensive method for sharing information with a wider audience.

**Talk**

## Models, minerals and methods – the handling with geoscientific objects in the public

**Birgit Kreher-Hartmann**

*Friedrich-Schiller-University Jena, Germany*

Most of geoscientific collections and museums at universities in Germany started up from the end of 18. century to the end of 19. century. It was oblique to teach students not only by lectures but also by practice. Therefore a lot of models were built. Models to explain geology, structures, crystallographic shapes and morphologies, twin laws, petrological processes, atomic structures and so on. Every collection and museums hosts not only minerals and fossils and rocks but also hundreds of models. And also mostly a collection of old, sometimes malfunctioned equipment. What should we do with them in the 21. century, the digital century? To throw them away? That's the worst case! To store them in the museum? Okay, that's no creative solution. What about to use this mostly historic stuff to teach still students or pupils or to inform the public about geoscientific themes. To combine these objects with minerals and rocks and also modern techniques will be obviously the best solution!

The mineralogical collection at the University of Jena/Germany was founded in 1779. So there is existing a large potpourri of things which were used during more than 200 years of teaching. In this talk some examples will be presented how to use historic models, methods, minerals and equipment beside the academic daily routine. Projects with schools, with formers students starting a teacher career, with the non-collegiate visitors in the museum and with kids through all years. There will be given a résumé about the gained experience through the last twenty years and the change of use of this historic objects.

**Poster**

## Let´s play! – The use of Minecraft® to communicate the complexity of the deep subsurface to the public

**Stephan Steuer[1], Stephen Thorpe[2]**

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Minecraft® is an open world, sandbox-style 3D game that was first published in 2009. It allows the player to build its own world and constructions out of a number of cubic blocks. In the standard version, one block equals 1x1x1 meter in size. This world can then be interactively explored by the player, or, if published, by other players. According to Wikipedia the game was sold over 144,000,000 times.

This large number of users combined with the possibility of creating personal and predefined worlds led to the idea of using Minecraft® to present geologic 3D models to the public.

The British Geological Survey developed a FME®-workflow to convert structural 3D-Models from GoCAD into Minecraft® worlds, which we adapted. First the GoCAD-file is translated into a wavefront-obj-file (pointcloud). Minecraft® offers a wide range of possible block types. These types refer to different materials the block will consist of. For example, one block can be assigned different geological lithologies such as sandstone, granite, or quartz The points of the obj-file are then assigned these specific properties and converted into Minecraft® blocks. Finally, all the blocks are then combined into a Minecraft® world.

There is one limitation to consider however: while there is no limitation in the lateral extent, a Minecraft® world is only allowed to have a height of 255 blocks. Deep reaching underground models have to be scaled in order to look reasonable within the limitations of this Minecraft® vertical extent. We first scaled the original GoCAD-model by the factor 1/10 and then made the final adjustments within the FME®-workflow to use as much vertical space as possible. We will present examples for different geological 3D models realized as Minecraft® worlds, including examples from Germany and Great Britain.

Publishing geologic 3D models of the subsurface in the form of Minecraft® worlds enables us to reach a broad audience (only few people own a GoCAD license), it gives the user an opportunity to interactively explore the subsurface and the gaming background makes it easy to engage young people in the subsurface. Another advantage is to use the Minecraft® world in combination with a VR-system to intensify the experience of the subsurface.

**Talk**

## Science Communication - Examples and New Initiatives

**Gerold Wefer**

*MARUM - Zentrum für Marine Umweltwissenschaften, Germany*

It is undisputed that dialogue with the public should be an important concern of science. It should not be limited merely to the dissemination of scientific results, but should also describe the methods by which the findings are obtained. Compared to other disciplines, it is relatively easy to interest the public in topics related to geosciences. Almost everyone is interested in climate, volcanism, earthquakes and tsunamis, or is concerned about resources such as water, building materials and energy. The Year of Earth Sciences 2002 and the Year of the Seas and Oceans 2016/17 both provided important impulses for public outreach: festivals, interactive courses, an inland-water vessel on tour, as well as many web-based offers. Much has been achieved, but what still needs improvement is an even broader participation by scientists. To achieve this, science communication must become a more important element in science projects and programs, and the achievements of active scientists must be more widely recognized.

It is undisputed that dialogue with the public should be an important concern of science. It should not be limited merely to the dissemination of scientific results, but should also describe the methods by which the findings are obtained. Compared to other disciplines, it is relatively easy to interest the public in topics related to geosciences. Almost everyone is interested in climate, volcanism, earthquakes and tsunamis, or is concerned about resources such as water, building materials and energy. The Year of Earth Sciences 2002 and the Year of the Seas and Oceans 2016/17 both provided important impulses for public outreach: festivals, interactive courses, an inland-water vessel on tour, as well as many web-based offers. Much has been achieved, but what still needs improvement is an even broader participation by scientists. To achieve this, science communication must become a more important element in science projects and programs, and the achievements of active scientists must be more widely recognized.

**Talk**

## Public relation at university affiliated museums

**Anne Zacke, Fides Friedeberg, Renate Schumacher, Dana Vlcek, Mara Lönartz, Maurice Malcharzyk, Matthias Roos**

*Mineralogisches Museum der Universität Bonn, Germany*

The Museum of Mineralogy at the University of Bonn is one of the university's 12 museums and collections respectively. With four exhibition halls presenting more than 6,000 objects and more than 60,000 specimen in the cabinets it is one of the larger institutions within this group.

The approach of the team goes far beyond presenting objects. Like all museums today, we perform many tasks. A basic one is collecting, preserving and conserving: our objects need care, conservation and restoration. Nowadays, they are also digitalised and added to a database. This is a huge but essential task. Research is another main task of museums today. The objects are in a continual process of being scientifically investigated, and are thereby placed in a broader context in terms of their formation and/or origination.

In addition to the listed duties a fundamental function is to mediate between science and public. In times of 'fake news' and a growing distrust to official institutions/scientific findings (e.g. controversy about climate change) in parts of the public communication becomes of rising importance. On one hand side we implement this by using our objects as a translator: with exhibitions. Additionally to our permanent exhibitions we present changing special exhibitions. They help to highlight and explore different and sometimes surprising aspects around the main theme minerals. Besides classic topics like ‘Turmaline’ or ‘Minerals and Colours’, we invited our guests to explore exhibitions like ‘Minerals and Art’, ‘Eating, Drinking, and Crystals’ or – in our current exhibition – ‘Highlights of student’s fieldtrips’. The public is invited to visit these exhibitions and our guests explore they by their own. This is the classic way and it mainly attracts the already interest community. Media and social networks provide new/different opportunities for communication. We use these tools plus our museum educational service to successfully reach and attract new visitors on one hand side and to welcome our frequenters consistently on the other hand.

# Topic 16: Fluid-Rock Interactions

## 16a) Fluid-rock interaction: from mechanisms to rates – from atoms to plates

Talk

### Fluid-rock reactions in the Cu-S system: an experimental investigation of the mineral replacement of chalcopyrite by chalcocite

**Alok Chaudhari**, **Joël Brugger, Andrew Frierdich, Rahul Ram, Barbara Etschmann**

*School of Earth, Atmosphere and Environment, Monash University, Clayton, Melbourne, Australia*

The various phases in copper sulfide (Cu-S) system constitutes a group of ore-forming and economically important minerals. The copper sulfide system is particularly challenging to investigate experimentally due to the presence of a number of high-temperature polymorphs which cannot be quenched to ambient conditions; resulting in a poor understanding of the reaction mechanism and kinetics involving the high-temperature Cu-S polymorphs. A combined experimental approach – involving both *ex-situ* and *in-situ* methods are required to decipher all controls on the reaction mechanism and kinetics in the Cu-S system.

I have undertaken a systematic experimental investigation, studying the replacement of chalcopyrite by chalcocite under mild hydrothermal conditions (0-100 bars, 200-300°C) in an acidic chloride medium ($CuCl_2$+$H_2SO_4$) using small volume Ti autoclaves for varying run durations (2 hours – 2 weeks). In addition to laboratory hydrothermal experiments, several *in-situ* X-ray diffraction were also conducted at the Australian Synchrotron, tracking the evolution of chalcocite in the system throughout the experiment.

Electron backscattered imaging (BSE) of the run products reveal a pseudomorphic replacement of chalcopyrite by chalcocite/digenite in all of the run products. Rietveld analysis of the X-ray diffraction patterns (using TOPAS) of the run products revealed progressive replacement of chalcopyrite by chalcocite/digenite with increasing run duration. The chalcocite/digenite formed by the replacement of parent chalcopyrite exhibits extensive textural development, with a distinct reaction rim separating the two mineral phases, and the change in molar volume ($V_m$% = -37.77) during the replacement reaction; leads to the development of porosity and cracks. The textural diversity in the replaced phase suggested that the mineral replacement reaction has followed a coupled dissolution – reprecipitation (CDR) reaction mechanism. The dissolution of chalcopyrite is coupled with the reprecipitation of chalcocite/digenite in the system. *In-situ* X-ray diffraction experiments (up to 230°C) on the mineral replacement reaction show the formation of covellite (CuS), indicating the possibility of covellite being an intermediate phase in the mineral replacement reaction.

Talk

### Coupling between deformation, dehydration and transport properties in evaporites

**Florian Fusseis**, **Sina Marti, Berit Schwichtenberg, Ian Butler**

*The University of Edinburgh, United Kingdom*

Evaporites are key to the emplacement of tectonic nappes and the formation of thin-skinned orogenic systems, and are considered for the storage of heat-emitting nuclear waste and spent fuels. During burial evaporites undergo diagenesis and low-grade metamorphism, whereby they compact, deform and dehydrate. The associated microscale changes in mineralogy, rock fabrics and porosity affect the hydraulic, chemical and mechanical (HCM) behaviour of evaporites on the grain scale and control the rocks' macroscale response to tectonic loading and heating. However, the complexities of these changes, and interdependencies between them, have never been determined nor quantified, which leaves our understanding of evaporite behaviour incomplete.

Halite and gypsum dominate evaporite HCM behaviour, whereby halite deformation and gypsum dehydration/deformation are coupled in a range of complex feedbacks: The negative volume change of the dehydrating sulphate and hydraulic fracturing induced by fluid overpressure affect the transport properties. Halite deforms predominantly by pressure solution creep and is therefore sensitive to the provision of undersaturated water. At the same time is gypsum dehydration strongly pressure-dependent and thereby the evaporite's dynamically evolving transport properties, which control the pore fluid pressure, directly feed back on the reaction kinetics. Ultimately, it is these coupled processes that determine the role of evaporites in tectonic processes and their suitability as host rocks for nuclear waste and spent fuel. However, the magnitude, both in time and space, of the feedbacks that arise in evaporites are essentially unconfirmed.

Here, we present first data on the temporal and spatial length scales of the HCM feedbacks controlling evaporite deformation under conditions involving those in shallow tectonic detachments. Our findings are based on experiments with bespoke x-ray transparent deformation rigs that were documented with time-resolved (i.e. 4-dimensional) x-ray microtomography at both, laboratory and synchrotron-based x-ray imaging facilities. We first explore halite deformation and gypsum dehydration/deformation separately and then show first results from two-phase deformation/heating experiments with halite/gypsum mixtures. By resolving the involved processes on the grain scale, our data significantly enhance our understanding of evaporite behaviour in thin skinned tectonics and as host rocks for heat emitting nuclear wastes and spent fuels. Our experiments further invite a discussion as to how other dehydration reactions might influence tectonic processes.

**Talk**

## Reaction-induced faulting in granulite causes earthquakes in the lower continental crust

**Sarah Incel[1,2], Loïc Labrousse[3], Nadège Hilairet[4], Timm John[5], Julien Gasc[2], Feng Shi[6], Yanbin Wang[6], Torgeir B. Andersen[7], François Renard[1], Bjørn Jamtveit[1], Alexandre Schubnel[2]**

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Pseudotachylite-networks in granulites on Holsnøy in the Bergen Arcs, SW Norway, and seismic tomography of the Tibetan plateau reveal that earthquakes were triggered even at the high temperature/high pressure conditions of the lower continental crust. Both, field and geophysical observations, demonstrate a strong link between the nucleation of intermediate-depth earthquakes and areas of partial eclogitization within nominally anhydrous granulitic lower crust. This study presents four deformation experiments performed on granulite samples from Holsnøy. To accelerate reaction kinetics, which is very slow in dry rocks, we applied confining pressures of 2.5-3 GPa and temperatures in the range 995-1225 K, significantly higher than the expected eclogitization conditions of the Bergen Arcs (pressure= 1.5-2 GPa, temperature= 923-973 K). Based on the mechanical data, micro- and nanostructural observations, and recorded acoustic emissions, we were able to correlate the degree of eclogitization to the rheological behavior of the samples. Depending on the net eclogitization rate relative to the deformation rate ($5 \cdot 10^{-5}$ $s^{-1}$) the sample either behaved strong and ductile if no reaction occurred, mainly brittle when the rate of eclogitization was slow, or mostly weak ductile when the rate of eclogitization was fast. Our experimental results emphasize that shear localization due to grain size reduction triggered by the breakdown of plagioclase under eclogite-facies conditions lead to brittle failure accompanied by acoustic emissions. These and other experiments on a variety of lithologies suggest that there could be one common mechanism that triggers intermediate and deep earthquakes.

**Poster**

## Exploring the feedback mechanisms between deformation, fluid flow and metamorphism along the subduction interface: The record within metasediments from the Western Alps

**Frederik Kirst, Jolien Linckens**

*Goethe-Universität Frankfurt, Germany*

In the Internal Western Alps of Switzerland and Italy, the Dent Blanche Basal Thrust (DBBT) represents a fossil subduction interface that was active during Paleogene subduction and accretion of Adriatic continental margin units and Piemont-Ligurian oceanic lithosphere. In the western Valtournenche of Italy, greenschist- to blueschist-facies metasediments are exposed along this boundary zone between continental rocks of the Dent Blanche nappe in the hanging wall and dominantly oceanic rocks of the Combin zone in the footwall.

We combine microstructural, textural and petrological analyses to constrain the tectonometamorphic evolution of a metasediment sample consisting of garnet + quartz + calcite + phengite + epidote/allanite + chlorite + titanite. The sample displays foliation-parallel quartz/calcite veins and top-to-the-NW shear bands in hand-specimen. BSE imaging reveals honeycomb garnets (quartz/calcite grains surrounded by fine webs of garnet) as well as spiral garnets. The rotation sense of spiral garnets indicates top-to-the-NW shearing. While matrix quartz shows a crystallographic preferred orientation (CPO) due to basal <a> and rhomb <a> slip, quartz grains within and close to garnet are more randomly oriented. In contrast, neighbouring calcite grains surrounded by thin bifurcations of garnet sometimes have similar orientations. Garnet displays a typical compositional zonation reflecting growth on the prograde path which is supported by pressure and temperature estimates from pseudosection modelling and garnet isopleth thermobarometry. Allanite occurs as oriented inclusions in garnet, within quartz inclusions in honeycomb garnet and in the core of epidote.

We interpret these observations as being the result of coupled deformation, fluid flow and prograde metamorphism during Paleogene activity of the now-exposed subduction interface of the DBBT: Foliation-parallel quartz/calcite veins probably formed due to infiltration of $SiO_2$- and $CO_2$-rich fluids prior to or coeval with prograde metamorphism. Such fluids may have led to fluid-assisted element transfer and formation of the observed microstructural relations and inclusion patterns. Thin garnet bifurcations along quartz and calcite grain boundaries and the formation of honeycomb garnet suggest high mobility of elements during garnet growth and prograde metamorphism. The presence of allanite indicates mobilization of light rare earth elements and precipitation from a fluid phase. The CPO of neighbouring calcite inclusions suggests brittle fracturing of calcite and subsequent garnet growth. Brittle behaviour of calcite during high-pressure metamorphism may have been the result of high pore-fluid pressures. The deduced shear senses are consistent with top-to-the-NW shearing during SE-directed subduction and subsequent foreland-directed exhumation at the base of the Dent Blanche nappe.

Poster

## Formulating Kinetic Monte Carlo models of crystal dissolution and growth

**Inna Kurganskaya[1,2], Rolf S Arvidson[1], Sergey V Churakov[2,3], Andreas Luttge[1,4]**

*[1]University of Bremen, Germany; [2]University of Bern, Switzerland; [3]Paul Scherrer Institute, Switzerland; [4]Rice University, USA*

Kinetic Monte Carlo (KMC) methods have a great potential in modelling complex solid-fluid systems [1]. The surface topography change, etch pit morphology and kinematics of atomic steps can be traced as a collective result of the large number of atomic scale chemical reactions. The challenging problem is the sufficient and correct input for the KMC models in terms of reaction rate list. The simplest solution coming to one's mind is to calculate all possible rates for all possible atomic configurations from Molecular Dynamics or ab initio calculations. This kind of studies were performed successfully for some systems, e.g. molecular crystals [2]. The mineral-fluid systems, however, exhibit much more complexity in terms of the number of structural and geometric controls of site reactivity. The approach we utilize is differentiating surface sites by the surface structure specific controls, including short and long range order, interfacial water and hydrogen bond structure [3], geometry of site and surrounding bonds, and other atomistic details inspired by the compiled data obtained from all relevant published ab initio and Molecular Dynamics studies. The new studies incorporate Grand Canonical Monte Carlo simulations as a powerful technique providing us the statistics of charged surface sites and adsorbed interfacial ions [4]. This approach allows us to directly incorporate solvent chemical composition controls of the dissolution kinetics.

[1] A. Luttge, R.S. Arvidson and C. Fischer, A Stochastic Treatment of Crystal Dissolution Kinetics (2013), Elements 9, 183-188

[2] S. Piana and J.D. Gale (2005), Understanding the Barriers to Crystal Growth: Dynamical Simulation of the Dissolution and Growth of Urea from Aqueous Solution, J. Am. Chem. Soc., 127, pp 1975–1982

[3] I. Kurganskaya and A. Luttge, Kinetic Monte Carlo Simulations of Silicate Dissolution: Model Complexity and Parametrization (2013) J. Phys. Chem. C, 2013, 117, 24894–24906.

[4] Churakov S. V., Labbez C., Pegado L. and Sulpizi M. (2014), J. Phys. Chem. C 118, 11752–11762.

Talk

## Vein-hosted Copper Deposits and Hydrothermal Processes of SW Ireland

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Copper has been exploited in SW Ireland for thousands of years. A recent increase in the demand for copper world-wide has led to renewed interest in these occurrences and their overall implication for copper metallogenesis in Ireland.

The study presented here focuses on historically mined vein-hosted copper deposits in southwest Ireland, identifying the dominant structural and geochemical controls to mineralisation in an Upper Devonian continental clastic sequence. This includes detailed maps of mining areas of West Cork, as well as a 3-dimensional model of the vein system and its structural relationship to mineralisation.

Detailed mapping in the Allihies vein-hosted Cu district (Beara Peninsula), including macro- and microstructural investigation, has revealed a brand new interpretation of the temporal development of deformed and faulted ore-bearing E-W striking early extensional (pre-orogenic) quartz veins which occur along large scale (km scale) E-W extensional faults. Minor, syn-Variscan quartz veining occurs along SW-NE trending faults and folds. These structural observations are compared with those from vein- and sediment-hosted deposits on Mizen Head and Sheep's Head peninsulas. Interpretation of GIS-supported satellite imagery and drone footage served as a key tool for the visualization of large and small scale structures.

Petrographic and fluid inclusion studies of selected samples of mineralised pre-Variscan quartz veins display a cluster of fluids that range from homogenisation temperatures ($T_h$ LV-L) of 270°C and salinities of about 10 Wt.% (NaCl eqv.) to a $T_h$ of 120°C and 27 Wt.% (NaCl eqv.), respectively the syn-Variscan veins have a $T_h$ of about 200°C and a salinity range between 9 and 19 Wt.% (NaCl eqv.). Most of the copper lodes consist of quartz-chlorite with syn-genetic chalcopyrite, minor bornite, chalcocite and tetrahedrite.

Stable isotope geochemistry has been undertaken to aid in understanding the source of sulphides and nature of the metal-bearing fluids. The $\delta^{34}S$ values of chalcopyrite are between -15.5 ‰ and -11.4 ‰, $\delta D_{SMOW}$ in quartz ranges from -27.3 ‰ to -22.0 ‰, and $\delta^{18}O_{SMOW}$ yielded a tight cluster between 12.8 ‰ to 13.9 ‰. These isotope ratios indicate a sedimentary to metamorphic fluid-rock interaction [1], possibly resulting from deep sourcing fluid systems migrating through basin sediments with a total thickness of about 6.7 km [2].

**References**

[1] Hoefs, J., 2015. Stable Isotope Geochemistry. (Seventh Edition) Springer International Publishing Switzerland 2015.

[2] Meere, P.A., Banks, D.A., 1997. Upper crustal fluid migration: an example from the Variscides of SW Ireland. J. Geol. Soc. Lond. 154, 975–985.

Talk

## Do injection-rate control the onset of fault reactivation?

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Fluid injections are known to induce earthquakes. To reduce induced-seismicity, regulators plan to decrease the injection-rate in the seismically active areas, such as Oklahoma. However, the influence of injection rate on fault reactivation remains poorly documented up to now. From a static point of view, elevated pore pressure can lead to slip reactivation on pre-existing fractures and faults when the coulomb failure point is reached. For instance, the reactivation of fault submitted to a background stress (τ0) is a function of the peak strength of the fault, i.e. the quasi-static effective friction coefficient (μeff).

In this study, we present new results about the influence of the injection rate on the onset of fault reactivation. Experiments were conducted on a saw-cut sample of westerly granite. The experimental fault was 8 cm length. Injections were conducted through a 2 mm diameter hole reaching the fault surface. Experiments were conducted at four different order magnitudes fluid pressure injection rates (from 1 MPa/minute to 1 GPa/minute), in a fault system submitted to 50 and 100 MPa confining pressure. Our results show that the peak fluid pressure leading to slip depends on injection rate. The faster the injection rate, the larger the peak fluid pressure leading to instability. Monitoring continuously the elastic wave speed across the fault during fluid injections allow us to image that large injection-rate induces local but intense fluid overpressures, which allow the reactivation of the entire fault. These results suggest that increasing the injection rate enhances fluid pressure heterogeneity in the fault system. Finally, the slip rate at the onset of slip increases drastically with the injection rate. These results suggest that the intensity of the fluid pressure perturbation rather than its size enhances the slip-rate, and could promote the nucleation of instability. Our experimental results demonstrate that reducing the injection rate promote a better homogeneity of the fluid pressure in the fault system, which could allow a better control of the resulting seismicity.

**Talk**

## Rate dissolution variability of sandstone calcite cement

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For a holistic understanding of the long-term usage and safety analysis of reservoir rocks it is crucial to understand the fundamental mineral reactions and their control mechanisms. Kinetic quantification of the processes involved with fluid-rock interactions are especially important for predicting the evolution of pore space in rocks subjected to fluid injection, such as in reservoir rocks. This study is inserted in the project ResKin – Reaction kinetics in reservoir rocks: upscaling and modelling, and our specific objective is to quantify the kinetics of calcite cement dissolution of sedimentary rocks.

The calcite cement selected for this study belongs to a fluvial-aeolian Rotliegend succession exposed near Bebertal (Flechtinge High, Germany) that was deposited in the same conditions as those that form the prolific gas reservoirs of the Southern Permian Basin[1,2]. Optical microscopy, SEM-BSE images and Cathodoluminescence analysis of the unreacted samples showed that although the calcite cement patches were composed of single crystals, two types of cement were present. We hypothesized that these different types of cement would react differently to fluid input. We used polished thick-sections of plug samples for dissolution experiments in a flow-through cell using a 2 mmol $Na_2CO_3$ solution (pH = 8.6, T≈ 21°C), for 7 reaction intervals (3 to 32 hours). Before and after each experiment the sample's topography changes were mapped using a vertical scanning interferometer (VSI). High-resolution surface maps are subsequently used to calculate surface dissolution rates[3].

After experiments, VSI images revealed an increase of the surface roughness in the cement patches. Detailed analysis of the rate dissolution variability in between the calcite cement patches and the intravariability of each cement patch related to chemical composition variability in the samples will be presented.

[1]Fischer, C., Gaupp, R., Dimke, M., Sill, O., 2007. A 3D high resolution model of bounding surfaces in aelian-fluvial deposits: An outcrop analogue study from the Permian Rotliegend, Northern Germany. Journal of Petroleum Geology, 30(3), 257–273.

[2]Fischer, C.; Dunkl, I.; von Eynatten, H.; Wijbrans, J. R.; Gaupp, R., 2012. Products and timing of diagenetic processes in Upper Rotliegend sandstones from Bebertal (North German Basin, Parchim Formation, Flechtingen High, Germany). Geological Magazine, 149 (5), 827-840.

[3]Luttge, A., and Bolton, E., 1999. An interferometric study of the dissolution kinetics of anorthite : The role of reactive surface area. American Jourbnal of Science, 299, 652–678.

Talk

## Feldspar surface evolution during solid-fluid reactions - a kinetic Monte Carlo study

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The avoidance and social proscription of nuclear power in Germany still does not solve the problem of nuclear waste management, which is currently one of the major environmental issues in central Europe. Due to minor knowledge about chemical stability and durability of different rock formations under different conditions, there is a huge demand in knowledge of dissolution mechanisms of minerals in nature. As most important rock forming mineral on earth, Feldspars should enjoy a special attention in the research of dissolution kinetics of materials and their solid-fluid reactions.

While lots of experimental studies, conducted in the field of dissolution mechanics deliver results of only one or a handful of different environmental conditions (e.g. pH, temperature, pressure), like Kampman et al.(2009)[2] , and are time consuming as well, simulation techniques like kinetic monte carlo (KMC) studies are able to deliver predictions of surface evolution under different conditions as well. The major advantages of KMC simulations are the parameter variability and the minor time consumption compared to experimental studies.

Faster computational power and better algorithms allow the advance of a model, wrote by Zhang and Luttge (2009)[1], to a much bigger system size. Furthermore, the addition of the albite – orthoclase solid solution is completing the full range of feldspar minerals. While the first aim of this study is, to compare the computations of the model with existing results by experiments, the second and more important application is the prediction of overall dissolution rates and surface reaction caused by screw dislocations and resulting dissolution stepwaves. This leads to a greater knowledge of processes including dissolving matter and is another step to understand, which parameters influence chemical stability of minerals most.

[1] Zhang, L., Luttge, A. A Theoretical approach to evaluating plagioclase dissolution mechanisms. *GCA* 73, 2832-2849. (2009)

[2]Kampman et al., Feldspar dissolution kinetics and Gibbs free energy dependence in a $CO_2$-enriched groundwater system, Green River, Utah. Earth and Planetary Science Letters Volume 284, Issues 3–4, Pages 473-488. (2009)

Talk

## Evidence for selective tungsten enrichment in different sections of altered oceanic crust

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The geochemical behaviour of W in different tectonic settings has already been intensively studied. However, it remains uncertain, whether all processes that potentially affect the geochemical cycle of W, i.e., by fractionating W from Th, U and Ta have already been fully identified. The ratios of W/Th, W/Ta, and W/U have long been regarded as being constant in most silicate reservoirs and were taken to mass-balance the W cycle. Recently, W enrichments relative to Th and Ta in many arc lavas have been found and were explained by fluid-induced W mobility in the subarc mantle wedge [1]. However, very little is known, as to whether hydrothermal alteration of the oceanic crust on its path to the subduction factory could already trigger W redistribution and enrichment in distinct portions in the altered oceanic crust (AOC). Since AOC covers more than 60% of the earth's surface and is known to act as sink or source for various elements, solving this question is of great importance for accurately constraining the geochemical cycle of W and related geochemical problems.

Here, we present high-precision W-Th-U-Ta data obtained by isotope dilution for samples from IODP hole 1256D. This segment of oceanic crust formed at the Cocos-Pacific plate boundary at 15 Ma during an interval of superfast spreading-rates. It is the first borehole comprising a complete section of upper oceanic crust down to the gabbros [2]. The sample suite includes well characterised samples covering all major alteration styles within the upper as well as the uppermost part of the lower oceanic crust at a high depth resolution. All measurements were performed by isotope dilution using mixed U-Th and W-Ta-Zr-Hf-Lu tracers with a Thermo Neptune MC-ICPMS at the University of Cologne.

Our results demonstrate that the fractionation of W from Th, U, and Ta within AOC is resolvable, indicating a progressive enrichment of W in the Lava and Sheeted Dike Complex sections of Hole 1256D. Additionally, elemental ratios of W/Th, Ta/W and W/U show now overlap with pristine MORB compositions and indicate even larger W enrichment than reported for arc lavas worldwide that were analysed in previous studies [1]. Consequently, the enrichment of W seen in arc lavas may partially mirror W enrichment in subducted altered oceanic crust that significantly contributes towards the trace element inventory of arc lavas.

[1] König et al. (2011) Geochimica et Cosmochimica Acta, 75 2119-2136

[2] Wilson et al. (2006) Science, 312, 1016–1020

Poster

## Tectonometamorphic and hydraulic processes along a fossil subduction plate interface gleaned from detailed mapping in the northern Mirdita Ophiolites (Bajram Curr, Albania)

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The obduction of ophiolites formed at mid-oceanic ridges onto passive margins is preceded by intraoceanic subduction. During incipient subduction, metamorphic soles with HT-assemblages form along the plate interface by overthrusting fluid-rich lower-plate material with hot, dry ultramafics of the upper plate. As lower plate material undergoes prograde metamorphism and dewatering, fluids are transferred along the plate interface and into the upper plate, assisting serpentinisation of upper plate mantle. To better understand interrelated tectonometamorphic and hydraulic processes associated with incipient intraoceanic subduction, we mapped c. 65 $km^2$ along a well-preserved subduction plate interface in the northern part of the Mirdita Ophiolite near Bajram Curr, Albania. The Mirdita massif forms part of the Western Vardar Ophiolite Unit, cropping out along the entire length of the Balkan Peninsula. Oceanic lithosphere formed in the Triassic to Jurassic and was obducted onto the Adriatic passive margin by the Kimmeridgian to Tithonian. Obduction was associated with progressive incorporation of lower plate material into a several km thick tectonic mélange at the base of the obducting ophiolite. Within the tectonic mélange, we distinguished several SE-dipping units. Successions of sub-greenschist-facies turbiditic slates and quartz-bearing to subordinately calcareous arenites dominate the structurally lower parts. Strata are often surprisingly coherent; a scaly fabric is only developed locally. Structurally higher parts of the mélange contain intercalations of quartz-sericite schists, calc-schists, meta-cherts and chlorite schists, indicating greenschist-facies conditions. Here, deformation is more intense, producing tight to isoclinal folds with mostly NE-plunging fold axes. Discontinuous lenses of serpentinite are interpreted as basally accreted slivers. The structurally highest parts of the mélange, preserved only locally, consist of amphibole-bearing paragneiss. We hence observe an inverted metamorphic gradient, typical of metamorphic soles worldwide. The base of the coherent upper plate ultramafics, forming the actual plate interface, dips SE and locally crosscuts NE-SW-striking folds within the underlying mélange. The structurally lowermost parts are harzburgites with relic protomylonitic fabrics defined by finegrained matrix Ol and porphyroclasts of OPx. Arrays of abundant, systematically oriented and mm- to cm-thick veins crosscut the basal harzburgites. Thin sections show the veins to consist of fibrous serpentine and an opaque phase. Vein density substantially decreases upsection. There, massive harzburgites include dunite lenses containing podiform chromites. Our observations hence suggest that serpentinisation of peridotites by hydraulic fracturing is strongly localized along and immediately above the subduction interface and that this process is linked to dewatering of the downgoing material, which itself undergoes prograde metamorphism.

Talk

## Dissolution Kinetics near Etch Pits – a Kinetic Monte Carlo Study

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The prediction of material flux from the crystal surface into the solution or melt is a relevant topic for material and earth sciences. It is known from dissolution experiments that the rates of this material flux are not constant but can vary over two orders of magnitude in the same mineral. Neither is reactivity distributed homogeneously over the crystal surface. Rather, during the initial stages of dissolution, etch pits form. Their subsequent growth and interaction leads to complex surface topographies.

Our theoretical understanding of the surface reactivity of crystals is based on the dissolution stepwave model [1]: etch pits form around lattice defects, the reactive surface sites driving the dissolution process self-replicate and move in trains of steps over the surface, resulting in the overall surface retreat. The velocities of these steps can then be predicted as a function of distance to the generating defect. However, this model offers no insight so far into the mechanistic processes involved in the generation and further interaction of these steps. To investigate this, we selectively examine smaller partitions of the whole system.

In this study, we computationally examine the early stages of crystal dissolution via kinetic Monte Carlo (kMC) simulations. Of specific interest is the development of the initially flat surface around a lattice defect. We use a Kossel crystal and a calcite 104 cleavage face. The development of etch pits around pre-defined defects is modelled stochastically by assigning probabilities to the dissolution of different types of reactive surface sites. We then focus on the examination of processes happening close to the etch pit center, including the temporal development of etch pit depth as well as the interaction of several steps in close vicinity of the hollow core. We vary model parameters such as the rates of kink site generation and the dissolution at kink sites and examine how this influences the kink site density and local corresponding dissolution rates. From these analyses, we seek to gain a more detailed understanding of the influence of kink site nucleation on the overall dissolution process.

[1] Lasaga, A. C., Luttge, A., 2001. Variation of crystal dissolution rate based on a dissolution stepwave model. Science 291(5512), 2400-2404.

Poster

## A retrograde epidote-amphibolite shear zone of Storekorsenes, Norway

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Motivation: Our aim is to understand the causes of the varying texture, structure and mineralogical composition, within a relatively small zone range, of rocks with the same protolith/precursor.

Object of our study is an outcrop with a very well preserved localisation of deformation materialised by a shear zone. The outcrop is located in the northernmost part of Norway, part of the Scandinavian Caledonides and represents one of many thrust sheets, formed during the Caledonian orogeny. Three samples, collected from different parts of the outcrop, were expected to represent a deformational sequence from undeformed to highly deformed epidote-amphibolite. A mineralogical investigation with an optical microscope and electron microprobe unravelled the evolution of the rock. Unexpected discoveries leave the interpretation of the origin of the outcrop controversial and question the old interpretation of the formation of the Kallak Nappe Complex.

Results: The undeformed sample represents diagnostic assemblage for metagabbro in the epidote-amphibolite facies (Onuki et al., 1977). For the highly deformed sample, we turned our attention to its changed mineral assemblage and structure. These are compatible with results expected from a fluid rock interaction and hydration reaction during a shear zone formation. The structurally intermediate sample was removed from the picture of a deformational sequence due to its incompatible mineralogical and textural properties. The absence of some of the main components in the other samples – minerals of the epidote-group - may be explained by the chemical inhomogeneity of the protolith/precursor. A reasonable assumption, if we take into account that protolith is an instance of layered gabbro. The chemical distribution of Mn, following the pattern of prograde metamorphose, discordant with that of the other samples, suggests a theory of xenomorphic origin of the sample. In the same outcrop we observe mineralogical and structural changes expected as a result of processes associated with a shear zone formation, as well as other unexpected findings, underscoring the complexity of the region's evolution.

Talk

## Rare earth element speciation in aqueous brines under subduction zone conditions: Ab-initio molecular dynamics simulations and free energy exploration

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The rare-earth-elements (REE) fractionation patterns are used in geochemistry to characterize geological processes, especially of subduction-related magmatism. Experimental data show that the REE signature of high-grade metamorphic rocks is modulated by the presence of aqueous fluids [1]. The REE mobility is controlled by the capacity of an aqueous fluid to host these elements in form of solute species. The formation of such species depends on the presence of ligands such as $Cl^-$, $F^-$ or $CO_3^{2-}$.

So far, many REE speciation models for high temperature, T, and pressure, P, conditions rely on the extrapolation from thermodynamic data at ambient conditions[2]. In some cases, the available high P/T experimental data show large deviations from these extrapolations[3], which underlines the necessity to study thermodynamic properties at the relevant conditions. It is experimentally very challenging or even impossible today to gain thermodynamic data in-situ at these P/T conditions. Therefore, first-principles molecular dynamics (MD) simulations have become an important tool to investigate fluid properties at extreme conditions.

Here, first-principles MD simulations in combination with thermodynamic integration (TI)[4] are used to derive equilibrium constants of dissociation reactions of different Y-Cl species. To understand the behavior of the heavy REEs in subduction fluids with high salinity we modeled a system containing 84 $H_2O$, 1 $YCl_3$ and 3 NaCl. We are able to show in accordance to experimental data[5] that $YCl(H_2O)_7^{2+}YCl_2(H_2O)_6^{+}$are the main stable Y-Cl aqueous species at ambient conditions. At high temperature and pressure conditions the complexation of Y by Cl increases and we find five different stable complexes. Our results indicate that $[YCl_3(H_2O)_3]_{aq}$ is the major Y-Cl species at 1.5 GPa and 800°C in a two molal NaCl brine. Finally, we will extrapolate the stability constants derived from the TI to the standard state at infinite dilution and calculate species distribution depending on the chlorine activity.

1.Tsay, A., Zajacz, Z. & Sanchez-Valle, C.. *Earth Planet. Sci. Lett.* **398,** 101–112 (2014).

2. wood, S. A.. *Chem. Geol.* **82,** 159–186 (1990).

3. Migdisov, A., Williams-Jones, A. E., Brugger, J. & Caporuscio, F. A. *Chem. Geol.* **439,** 13–42 (2016).

4.Sprik, M. & Ciccotti, G.. *J. Chem. Phys.* **109,** 7737–7744 (1998).

5. Rudolph, W. W. & Irmer, G.. *Dalton Trans.* **44,** 18492–18505 (2015).

**Talk**

## Partially open grain and phase boundaries as fluid pathways in magmatic and metamorphic rocks: new observations

**Richard Wirth[1], Jörn H. Kruhl[2], Luiz F.G. Morales[3], Anja Schreiber[1]**

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Combined TEM and SEM/FIB sequential imaging of quartz grain boundaries from contact and regional metamorphic rocks show that most of the grain boundaries are open on the nanometre scale. Three types of voids occur: (i) roughly 40 to 500 nm wide, open zones parallel to the grain boundaries; (ii) cavities of variable shape and up to micrometre size along the open grain boundaries; and (iii) cone-shaped, nanometre-sized depressions at sites where dislocation lines meet the open grain boundaries.

The significance of these structures is proven by their wide occurrence, also along phase boundaries between quartz, K-feldspar, plagioclase, amphibole, pyroxene and calcite and in a variety of rock types: monzonite, basalt, metagabbro, felsic granulite, UHP jadeite quartzite, marble and hydrothermal quartz. The up to 600 nm wide, open grain and phase boundaries and the even larger dissolution cavities are partly filled by secondary minerals, such as amphiboles, biotite, quartz, chlorite and vermiculite. These minerals do not replace the neighbouring grains but fill the already open boundary, as proven by growth textures. This argues for dissolution-precipitation processes caused by fluid circulation in a connected network of porosity, partly already under mid-crustal conditions.

The grain- and phase-boundary-parallel open zones are suggested to be generated by thermal contraction at temperatures below the threshold temperatures of diffusion of the involved minerals, and kept open against confining pressure and decompression expansion, due to the anisotropy of thermal contraction, even at pressures of several hundred MPa.

The importance of the investigated phenomenon is rooted in the probably large effect of networks of partially open grain and phase boundaries on permeability, reactivity, elasticity, strength, shear resistance, and weathering of rocks. Rock strength and elasticity may highly depend on the amount of open grain and phase boundaries and the amount and type of filling. Specifically during uplift and cooling, rocks with strong crystal preferred orientations and anisotropy of grain and phase boundary networks may channelize fluids and, consequently, strongly influence fluid flow in the middle and upper continental crust. The same probably holds for the oceanic crust. Not least, open grain and phase boundaries most likely highly governs the weathering behaviour of rocks, again in relation to fabric and fabric anisotropy.

# 16b) Solid-fluid reactions in technical and Earth systems

**Poster**

## Investigation of the influence of fluid flow on the mass transport on the microscale using 3D numerical simulation

**Robert Büssing[1], Gerhard Bartzke[1], Cornelius Fischer[2], Adreas Lüttge[1], Katrin Huhn-Frehers[1]**

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Nuclear waste are embedded in ceramic materials to shield the environment from the radiation while being deposited in the underground. Dependent on the surrounding host rock the ceramic is subjected to dissolvent groundwater flows and should therefore be highly resistant against dissolution. Commonly laboratory based experiments are carried out to verify the resistivity of the ceramic material with regard to dissolution. However, it is challenging to directly determine the interaction between fluid movement and mass transport on the microscale.

In order to overcome this difficulty we present a 3D numerical hydrodynamic continuum study in which the fluid flow and mass transport over a ceramic surface are investigated. Using the finite volume method implemented in the open-source code OpenFOAM, we conducted a total of 13 experiments with changing topographies to test the influence of changing surface roughness values onto the fluid flow and mass transport. The mean flow velocity over the pyrochlore surface was 6.25x10-10 m/s. We used the steady-state flow field to simulate the the advective mass transport. Therefore, a tracer was injected into the domain at the left boundary. To investigate the advective mixing between the horizontal flow and the fluid in the surface depression we saturate the depressions with a scalar tracer and observe the advective removal of the tracer. All transport simulations were conducted for 40000 s total runtime, after which the effluent concentration reached a steady threshold.

The results of the hydrodynamic model show the development of a cavity flow in the pore space dividing the flow into an internal flow and an external flow. Likewise the transport simulation shows a preferred transport across the surface, with little mixing into the surface depressions. These effects become more pronounced with increasing surface roughness. This limited supply of fresh, unsaturated fluid will lead to the development of a saturated layer covering the pore space and hence slowing further surface dissolution and ultimately might affect the dissolution rate of a ceramic surface. Consequently, by the numerical models it was possible to observe the development of the flow field within the ceramic, allowing for a better understanding of the hydrodynamic processes in the pore space.

**Talk**

## New insights into the glass corrosion process by in situ confocal Raman spectroscopy

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Borosilicate glass is the preferred material for the immobilization of high-level nuclear waste and an important material for various industries. Silicate glasses, however, are prone to corrosion by aqueous solutions, which is reflected by the formation of surface alteration layers (SALs) that are assumed to represent a chemically leached, restructured residual glass. However, there are several inconsistencies with this interpretation such as, for instance, the observation of an atomically sharp interface between the SAL and the underlying glass or the formation of structural and chemical patterns in the SAL, which both cannot be explained by a diffusion-controlled corrosion mechanism.

Experimentally, glass-water reactions are typically investigated under controlled experimental conditions and by *post mortem* analysis of the experimental solution after quenching it to room temperature and/or the solid reaction products after quenching, drying, and mechanical sectioning. Quenching is a crucial shortcoming of such a *post mortem* experimental procedure, since the main corrosion product of silicate glasses is a hydrous amorphous silica gel that undergoes significant chemical and structural changes. As a matter of fact, a missing component of our current experimental and analytical strategies is the investigation of glass-water reactions at the microscopic to molecular level without disturbing or interrupting them.

In this study, we performed novel confocal hyperspectral Raman experiments to *in situ* study the reaction between a ternary borosilicate glass and a 0.5*M* bicarbonate solution at 85°C. To determine the local pH *in situ*, i.e., space-resolved at the micrometre scale, we used the speciation of bicarbonate and carbonate ions in solution, which is highly dependent on the pH. At the beginning of the reaction, we observed a thin boundary layer at the surface of the glass with higher pH values relative to the bulk solution. At this stage the glass dissolved congruently. After the formation of an SAL, we found an even higher pH within a water-rich interfacial solution located between the SAL and the underlying glass. A sudden drop of the reaction rate was observed after the SAL thickness had reached ~30 µm. By exchanging the solution with a deuterated bicarbonate solution, we were able to follow the transport of $D_2O$/OD through the SAL and observed that water transport to and from the interfacial solution was not rate-limiting. The *in situ* data supports an interface-coupled dissolution-reprecipitation model for the formation of the SAL and casts doubts on the validity of published kinetic glass corrosion models.

Talk

## Kinetics of pipeline steel corrosion studied by Raman spectroscopy coupled Vertical Scanning Interferometry

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The lifetime of a material such as pipeline steel requires precise quantification, as premature material failure can result in economic and environmental catastrophes. Corrosion is often a localized phenomenon due to defects and impurities[1], methods that are capable of providing information on these heterogeneities is of large interest. This study presents a new method using Raman spectroscopy coupled with vertical scanning interferometry (RC-VSI) delivering a wealth of qualitative observations and quantitative data of the corrosion kinetics.

The setup is capable of measuring the rate variations across the entire surface and identifying the (mineral) phases on the metal surface. We utilize a tested concept from the mineralogy applications[2,3] that allows variation of rates to be visualized in rate maps and rate spectra. The Raman maps can then be linked not only to the topography, but also to the rate maps providing a direct correlation between reaction kinetics and surface composition. Adapting this concept[2,3] to the corrosion of steel enables furthermore the generation of rust maps, rust volume and volume of steel material lost.

Now, we are able to provide a comprehensive material-characteristic quantification of the corrosion behavior. Here, we demonstrate the procedure on an API X70 steel sample in a 3.5% NaCl solution. The overall material-characteristic corrosion behavior is seen in two rate domains. The rate maps allow the identification of areas with high corrosion rates where micro pits form macro pits. A detailed investigation with the coupled Raman spectrometer of a corrosion pit shows the distribution of Magnetite and Fe-hydroxides.

**References**

1. Machnikova, E., Arvidson, R., Fischer, C., Luttge, A. & Whitmire, K. Insights into the kinetics of acid corrosion reactions from direct analysis of surface morphology. *Geochimica et Cosmochimica Acta* **72** (2008).

2. Lüttge, A., Arvidson, R.S. & Fischer, C. Fundamental Controls of Dissolution Rate Spectra: Comparisons of Model and Experimental Results. *Procedia Earth and Planetary Science* **7,** 537–540 (2013).

3. Fischer, C. & Luttge, A. Beyond the conventional understanding of water–rock reactivity. *Earth and Planetary Science Letters* **457,** 100–105 (2017).

Talk

## Fundamental problems in mineral-fluid reaction kinetics modelling: system size, parameterization, complexity and scalability

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The geo- and material sciences are multi-faceted interdisciplinary fields covering many processes taking place in natural and man-made systems. During the last few decades our research received a boost of computational and analytical technologies that made this position even more prominent. Now, we face the challenging problem of linking the knowledge and data generated by using techniques operating at different spatial and temporal scales. Many studies focused on reaction kinetics were conducted by using Atomic Force Microscopy operating at near atomic resolution. Extension of such the nano to micron size observations to the macroscopic phenomena is achieved by Vertical Scanning Interferometry that operates at larger scales covering micron to millimetre ranges. The kinematics of the reactive features observed at this range of scales, e.g., macrosteps, etch pit coalescence, pit clustering, and dissolution at grain boundaries, show scale-dependent characteristics [1].

The theoretical understanding of the mineral-fluid interaction is significantly improved by using atomistic modelling. At the smallest scale, i.e., the atomistic structure of the mineral-fluid interface can be modelled by ab initio and Molecular Dynamics methods and covers system sizes of 100 to 1000 atoms. We utilize the power of the Kinetic Monte Carlo models to relate the variety of experimentally observed dissolution scenarios to well-defined atomic scale processes: atomic detachments, attachments, hollow core opening etc. The development of the KMC models requires us to solve a number of problems: finding proper modelling parameters, choosing the most optimal model complexity [2], and find ways to interpret and scale up the modelling results [3]. We present here the summary of the results of the work we done in this direction applied to different materials: carbonates [3], quartz [2], phyllosilicates [4]. We also discuss the future directions of this study and its relations to the other computational and experimental techniques operating at different scales.

[1] A. Luttge, R.S. Arvidson and C. Fischer, A Stochastic Treatment of Crystal Dissolution Kinetics (2013), Elements 9, 183-188

[2] I. Kurganskaya and A. Luttge, Kinetic Monte Carlo Simulations of Silicate Dissolution: Model Complexity and Parametrization (2013) J. Phys. Chem. C, 2013, 117, 24894–24906.

[3] I. Kurganskaya and A. Luttge, Kinetic Monte Carlo Approach To Study Carbonate Dissolution (2016). J. Phys. Chem. C, 2016, 120 (12), pp 6482–6492

[4] I. Kurganskaya and A. Luttge, A comprehensive stochastic model of phyllosilicate dissolution: Structure and kinematics of etch pits formed on muscovite basal face, Geochim. Cosmochim. Acta 120, 545-560.

Poster

## Investigation of the impact of $CO_2$ and associated compounds on the Grey Wesersandstone in the presence of formation waters at non ambient conditions

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Within the BMBF (German Federal Ministry for Economic Affairs and Energy) research project CLUSTER [1] combined experimental mineralogical-geochemical and geomechanical investigations of the interaction of $CO_2$ streams with sandstone and cements at the injection site are carried out.

The chosen sandstone belongs to the Trendelburg beds of the Solling formation and is cemented with quartz [2]. Samples were saturated with chloride rich brine (~230 g/L NaCl, 15 g/L $CaCl_2$, 5 g/L $MgCl_2$), exposed to non-ambient conditions being expected at the point of injection (333 K, 16 MPa) and treated with supercritical $CO_2$ (including associated compounds, e.g. $NO_2$, $SO_2$), for several weeks (~5 wks).

To investigate the impact of the treatment the sandstone samples were characterized, with geomechanical methods and with optical (3D digital microscopy) and electron microscopy. The analysis showed that fracture planes and the morphology of grains differed strongly depending whether the samples were treated or not. High resolution SEM analysis yet showed that the treatment did show observable impacts of the treatment under the given non-ambient conditions in the autoclave [3].

References:

[1] CLUSTER. Joint research project CLUSTER. Available online: www.bgr.bund.de/CLUSTER/ (accessed on 13.10.2017) [2] J. Weber, W. Ricken: Quartz cementation and related sedimentary architecture of the Triassic Solling Formation, Reinhardswald Basin, Germany, Sedimentary Geology 175 (2005) 459–477 [3] A. Neumann, K. Svensson, H. Pöllmann, F. Menezes, C. Lempp, Mineralogical analyses of the impact of CO2 and associated compounds on sandstone in the presence of formatio

Poster

## The effect of orientation and location of calcite dissolution kinetics

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Calcite ($CaCO_3$) is one of the most abundant and readily reactive mineral in almost all types of crustal rocks. Its 104 cleavage has been useful for unravelling the different mechanisms of mineral dissolution, such as the formation of etch pits and stepwaves[1]. Though, in nature the 104 surface will not be the sole exposed surface. Previous studies showed that the dissolution of calcite faces at different angles to the cleavage surface results in a significantly different evolution of surface morphologies[2] and is variable for different reaction times[3]. Moreover, grain edges (in rocks, typically referred as the grain boundaries) may yield a more efficient means of generating steps that contribute to mineral dissolution[1]. Our study seeks to quantify the variability of calcite dissolution rates with respect to the location (middle and edge of the sample) and orientation of the sample faces. We study the dissolution kinetics here with a special focus on the corner of the crystal (the corners where the obtuse and acute angles meet).

Calcite single crystals are cross-cut parallel to the c-axis. Samples are reacted in a flow-through cell using a 2 mmol $Na_2CO_3$ solution, equilibrated with respect to $CO_2$ to obtain a constant pH of ≈ 8,6. The flow rate is maintained high enough to avoid any diffusion mechanisms to occur (>0.6 mL/min). Surface topography data are collected before and after experiments using Vertical Scanning Interferometry (VSI). VSI images provide the database for the calculation of rate maps[4] from the surface height retreat at different experimental time steps.

This approach constitutes an extension to defect control of stepwave generation, as grain boundaries can be thought of as arrays of (3-dimensional) planar defect distributions, as opposed to that of linear (screw and edge) dislocations, and aims to link observations to an overarching theoretical framework for crystal dissolution.

[1]R. S. Arvidson, I. E. Ertan, J. E. Amonette, and A. Luttge, Geochim. Cosmochim. Acta 67, 1623 (2003).

[2]M. E. Smith, K. G. Knauss, and S. R. Higgins, Chem. Geol. 360–361, 10 (2013).

[3]J. Bisschop, D. K. Dysthe, C. V. Putnis, and B. Jamtveit, Geochim. Cosmochim. Acta 70, 1728 (2006).

[4] C. Fischer, R. S. Arvidson, and A. Lüttge, Geochim. Cosmochim. Acta 98, 177 (2012).

**Poster**

## Quartz habits and secondary pseudomorphs in the Grey Wesersandstein

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The Grey Wesersandstein from Germany is a typical triassic feldspatic sandstone [1] exhibiting secondary diagenentic modified evaporite lenses (SDME) with lower density and interesting mineralogical features. These SDME objects contain some secondary pseudomorphs of quartz after halite. These lenses (~1 mm to ~2 cm) in the sandstone are interpreted as a diagenetic process during which original NaCl was replaced by other sodium containing minerals like Albite. Halite was also replaced by $SiO_2$ (release from the alteration of feldspars) [2]. Due to this fact different grains and crystals of quartz occur in the sandstone [3]. First: Original quartz grains of the sandstone. Second: Secondary authigenic quartz crystals. Third: Pseudomorphs of quartz after Halite-crystal (hexaedric habit). Fourth: Typical etching cavities due to weathering effects. The following images show the different quartz habits and formations in the Grey Wesersandstein formation. In the performed investigations for evaluation of usage of Wesersandtein as a potential storage material, these different quartz crystals feature different geochemical and geomechanical properties. The formation and habit also differs from their varying origin. Almost rounded quartz grains in the sandstone, newly crystallized idiomorphic quartz and also pseudocubic and pseudomorphic quartz. Some newly formed quartz crystals show already etching pits as their faces are already under the influence of starting dissolution. Figure 1) Selected high resolution SEM images of the Grey Wesersandstone. Left: Typical etching cavities on quartz crystals also exhibiting in part crystal faces. Right: Authigenic quartz crystal covered with laminated clay minerals References

[1] J. Weber, W. Ricken: Quartz cementation and related sedimentary architecture of the Triassic Solling Formation, Reinhardswald Basin, Germany, Sedimentary Geology 175 (2005) 459–477 [2] Land, L. S., Milliken, K.: Regional loss of $SiO_2$ and $CaCO_3$, and gain of $K_2O$ during burial diagenesis of Gulf Coast mudrocks, USA. In: Worden R, Morad S, editors. Quartz cementation in sandstones, Int. Assoc Sed, Sp Publ, vol. 29, 2000, p. 183– 97. [3] A. Neumann, K. Svensson, H. Pöllmann, F. Menezes, C. Lempp, Mineralogical analyses of the impact of $CO_2$ and associated compounds on sandstone in the presence of formation waters at non ambient conditions, 40th ICMA Conference, Miami (2018).

**Poster**

## Study on Leakage around the Sarmashk Dam Foundation based on Site Geotechnical Properties and Rock Mass Structure

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From the Geotechnical viewpoint, the most significant factors for designing and constructing the reservoir dam can be considered to determine and assess the amount of water leaking from the under dam, the stability calculation of the dam body and foundation and identification of probable causes of unexpected water loss. In this study, the geotechnical and hydrological properties of the suggestion dam site in Sarmashk area has been considered. As such, firstly, the boreholes drilling points were determined based on the local investigations and field observations. Then, fourteen boreholes at the site of dam reservoir and five extra boreholes in the range of dam axis and its supports were drilled. At the same time as digging, geological data, i.e. geological complications, stratigraphy, geomorphology, and the features of the rock masses of the borehole points were recorded. Based on the data collected from the site, the geomechanical properties of the rocks and the geotechnical characteristics of the dam site were determined to design the engineering geological profile along the dam axis. The flow lines of water leakage from the dam sides and the under dam body were modeled for calculated the probable leak rate. The results showed that the rock mass properties were in a very good to excellent range based on RQD and RMR, Q and GSI classifications. Moreover, the permeability test in exploratory wells and the related calculations showed that the low permeability rate, except the surface weathered zones and crushed zones. Consequently, there will be no unexpected loss of water in the future based on the current study.

Poster

## Remobilization of geogenic contaminants in groundwater and mine waters in the former mining district city of Ouro Preto, Minas Gerais (SE, Brazil): a pilot study

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The *Quadrilátero Ferrifero*, or Iron Quadrangle of Brazil, is well known for the related mining activities that reach back to the XVII century and are closely tied to Brazils' colonial history. The regional occurrence of banded iron formations is the basis to this active mining province, and weathering of the iron- and gold-bearing rocks releases geogenic contaminants. For instance, elevated arsenic concentrations in sediments, surface waters, and waters from fractured aquifers have been recognized as a major source of geogenic water contamination, particularly as some of the affected aquifers are used for water production in the city of Ouro Preto (Minas Gerais).

Previous studies have found the As concentrations in the water of 4 mines in Ouro Preto to correlate to the amount of rainfall in the region. Arsenic concentrations are elevated during the wet austral summer, from circa December to March, and are negligibly low during the dry season. These results were interpreted to imply that As is mobilized within the unsaturated oxic zone during the dry season, and later transported and washed out during the wet season.

Our pilot study aims to identify the relevant processes that control As dynamics and (re)mobilization in the region of Ouro Preto. To do so, samples of aquifers with As bearing waters are compared with samples from ‚reference' aquifers, which are known to be void of As. With that intent, this pilot study contemplates (a) waters' major composition of cations and anions, and trace element composition, (b) As speciation for selected samples, (c) waters' stable isotopic signature, (d) suspended sediments geochemical composition, and (e) microbiome composition. These analyses will be completed by a time series of the stable isotopic composition of the waters, including rainfall, and the determination of water residence time from two deeper wells, to assess the role of hydraulics and groundwater evolution on the As dynamics. A first sampling campaign was carried out during the rainy season 2017/18, which will be completed by a second campaign during the dry season 2018.

Talk

## Clay Mineral Growth: A Kinetic Monte Carlo Study

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Clay minerals are one of the most abundant silicates that form under earth surface conditions. Therefore, they play a key role in weathering and diagenetic processes. Additionally, they play an important role in oil and gas reservoir analyses. Their small grain size makes them special for the use in technical and engineering applications, e.g. as nanocomposites. Therefore, a comprehensive understanding of these minerals, particularly of their formation and growth kinetics is important. Due to the recent increase in speed and decrease in cost, computer simulations can provide fast and reliable data without the need for large numbers of complex and time-consuming laboratory experiments. Kinetic Monte Carlo simulations can provide information about the growth and dissolution kinetics at atomic resolution with varying structural and chemical properties of the mineral.

In this study we develop a new kinetic Monte Carlo model of the clay mineral illite. Illite is chosen as an example of the large clay mineral group because as a dioctahedral sheet silicate it is closely related to the structure of micas, e.g., muscovite. For muscovite a functioning kMC model has already been published [1] and can be used as a basis for the new simulation. In contrast to the muscovite study, growth starting from an illite nucleus is be the focus of our work. The interlayer cations and their distribution play a key role in clay minerals as well as the charge distribution in the octahedral layer and, therefore need to be implemented into the simulation [2]. Another important aspect is the consideration of crystal defects such as screw dislocations and point defects for the growth kinetics. Such defects play an important role in crystal dissolution and may, therefore, influence the growth of clay minerals as well. The computer simulations yield new quantitative information on the reaction mechanisms and provide insight on such important questions as the limitations of clay mineral size.

[1] Kurganskaya I and Luttge A (2013) A comprehensive stochastic model of phyllosilicate dissolution: Structure and kinematics of etch pits formed on muscovite basal face. Geochimica et Cosmochimica Acta 120, pp. 545-560.

[2] Sainz-Diaz CI, Palin EJ, Hernandez-Laguna A and Dove MT (2004) Effect of the tetrahedral charge on the order-disorder of the cation distribution in the octahedral sheet of smectites and illites by computational methods. Clays and Clay Minerals, Vol. 52, No. 3, pp. 357-374.

**Talk**

## Sandstone-brine interaction and the formation of zeolites in experiments under geothermal conditions

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Enhanced geothermal systems (EGS) use open hole circulation, where hot, highly saline brines react with the reservoir rocks. Sandstone formations are one of the favourable targets because of their often high matrix permeability and even higher fracture permeability. Geochemical-mineralogical reaction of the highly saline brine with the reservoir sandstone could result in a change of the permeability with high impact on the geothermal circuit.

To understand the kinetic of rock-brine reactions arkosic sandstone samples with a fresh surface, representing fracture surfaces, have been treated with two molar Na-Cl, Na-Ca-Cl, or Ca-Cl solutions in batch-type experiments at 200 °C, and ~16 bar, in time series up to 60 days duration.

Depending on the experimental solution different zeolite phases formed during the experiments. The zeolite formation consumes clay minerals from the sandstone cementation and quartz from the clasts. Alkali cations for zeolite formation are provided from the solutions. Thus, type of zeolite phases and their chemical compositions depend strongly on the fluid composition. Accordingly, analcime precipitate in the experiments with pure Na-Cl solution close to its ideal composition of $NaAlSi_2O_6$ x $H_2O$. In the experiments with Na-Ca-Cl solution analcime and wairakite (ideal: $CaAl_2Si_4O_{12}$ x 2 $H_2O$) were formed. Here, analcime incorporates elevated amounts of Ca, and wairakite relatively high amounts of Na. In the pure Ca-Cl experiments, wairakite and epistilbite ($CaAl_2Si_6O_{16}$ x 5 $H_2O$) have formed on the sandstone surface. Both chemical compositions are nearly ideal.

Consequently, type and composition of zeolite phases can provide information about the temperature, pressure and fluid composition in the reservoir. Cation ratios in the zeolites give evidences of the fluid with which they have reacted. Since the reaction rate of zeolites is rather fast, changes in fluid composition will result in a rapid re-equilibration of the solids.

The reaction of the sandstone with the reservoir-like brine result in the formation of new zeolite phases, which can have a high impact on the permeability of a geothermal circuit and therefore for the live time of a geothermal installation.

**Poster**

## Arsenic dynamic across an iron mineral dominated redox transition zone

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Arsenic contaminated drinking water is a health problem affecting millions of people worldwide. Especially in the densely populated river valleys in South and South East Asia up to 200 million people are threatened by increased arsenic concentrations in drinking water from shallow aquifers. Although filter system established during the last two decades reduced the health effects significantly high arsenic concentrations are still a large public health concern. Through anthropogenic influenced changes in ground and surface water flow arsenic free aquifers are increasingly at risk of being contaminated. In order to keep the unmanageable consequences it is indispensable to better understand the arsenic dynamic within Holocene and Pleistocene aquifer.

In the area of South East Asia changes in redox conditions are mainly accepted as dominant trigger for arsenic release due reductive dissolution of iron oxides and oxyhydroxides and further ferric minerals. Despite intense research still process within the arsenic dynamic remain unknown. Especially the effects of small-scale mineralogical and geochemical alterations along redox transition zones are poorly investigated. The understanding of the solid phase transformation taking place along redox gradients is essential to explain and predict arsenic mobilization and retention processes.

Through analyse of sediment cores across the front of a redox transition zone it was possible to create a vertical profile of the solid-phase composition across several redox fingers in high spatial resolution. The comprehensive characterization of elemental and mineralogical composition along the redox gradients including distribution of arsenic carrier phases as well as variation of arsenic content and speciation offers new insights in the solid-fluid interface reactions in a natural system on small scales affecting arsenic dynamic. Specific analyses of iron minerals including valence state and speciation as well as type of structural bonding offer a better understanding of arsenic mobilization and retention processes and the related mineral-fluid interactions leading to solution and precipitation of arsenic hosting ferrous minerals.

The broad description of variations and alterations in solid phase composition enables a better understanding of arsenic dynamic and the environmental impact of anthropogenic induced redox changes. It was possible to identify redox zone specific mineral compositions related to arsenic cycling and estimate small-scale effects of redox dynamic and changing geochemistry on arsenic release and fixation. The work gives new insights in arsenic and iron cycling under redox changes and provides a better understanding of the behaviour of arsenic in natural systems.

Talk

## Rutile alteration and authigenic growth during fluid-rock interactions in metasandstones of the Moeda Formation, Minas Gerais, Brazil

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Microstructures, trace elements and U–Pb ages are presented from rutile grains in Moeda Formation sandstones (Quadrilátero Ferrífero, Minas Gerais, Brazil). The combined datasets suggest that originally detrital rutile was affected by two distinct fluid-mediated processes during the Transamazonia orogeny at 2.25 Ga, causing the formation of secondary grains with unusually high contents of Th (1–142 ppm) and rare-earth elements (ΣREE = 1–132 ppm), and with chondrite-normalized middle REE humps. Detrital rutile grains in sample A were altered by a coupled dissolution–reprecipitation process, resulting in porous grains having variable contents of rutile-compatible and -incompatible trace elements, e.g, Th (1–48 ppm), Zr (25–796 ppm), U (12–167 ppm), Cr (900–12878 ppm), W (143–3939 ppm), Nb (1148–6168 ppm). Rutile grains in sample B are mostly authigenic, and formed after dissolution of pre-existing detrital rutile grains and subsequent transport and homogenization of trace elements. These grains show anhedral shapes, contain numerous, randomly oriented muscovite laths, and show significantly lower, and less variable contents of trace elements compared to type-A rutile: Th (0.5–16 ppm), Zr (21–67 ppm), U (5.8–24 ppm), Cr (1379–3153 ppm), W (9.4–70 ppm), Nb (921–3058 ppm). Significant contents of Th and REE in sample B are explained by co-precipiation with $TiO_2$ aggregates prior to structural ripening. The close association of rutile with muscovite, the $MREE_N$ humps, and the results of Zr-in-rutile thermometry suggest that autigenic rutile formation and detrital rutile alteration in the investigated sandstones was mediated by (Na)-K–Si–P-bearing aqueous fluids at temperatures of about 490°C. The rutile $MREE_N$ humps are interpreted to result from the tetrad effect during leaching of spatially associated detrital zircon grains. Uranium–Pb ages of ≤2.25 Ga indicate that the fluid overprint started at the onset of the Transamazonian orogeny, perhaps related to the opening of the Sabará foreland basin.

# 16c) Subduction zone input, processes and output

**Poster**

## Preliminary experimental results on phase relations in the system $K_2O$-$Al_2O_3$-$SiO_2$-$H_2O$ at 8-12 GPa to understand phase relations after deep subduction of continental crust

**Dennis Berkels[1], Hans-Joachim Massonne[1], Thomas Fockenberg[2]**

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The occurrence of diamond-bearing felsic rocks from the Erzgebirge in Germany and the Kokchetav Massif in Kazakhstan indicates deep burial of continental crust material. It is likely that subduction of oceanic crust and lithospheric delamination, with lower crust involved after continent-continent collision, are possible mechanisms to generate these rocks. At pressures of about 10 GPa coesite transforms into stishovite and $KAlSi_3O_8$ with hollandite structure forms in crustal rocks resulting in densities exceeding those of the surrounding mantle with the consequence that such crustal rocks will be more deeply subducted. At least, preliminary thermodynamic calculations in the system $K_2O$-MgO-$Al_2O_3$-$SiO_2$-$H_2O$ (KMASH) with newly derived data show that K-hollandite and Si-wadeite should be potassium bearing phases coexisting with pyrope, dark mica and OH-topaz at pressures higher than 10 GPa. Dependent on the bulk composition, resembling those of metapelites, the whole-rock density can exceed a value of 3.4 g/cm³ that is likely for surrounding pyrolites.

The KMASH-system is suitable to understand the phase relations of pelitic and silicon-rich rocks. For this purpose and to optimize our preliminary thermodynamic calculations, experiments within this system will be undertaken at conditions of 8-12 GPa and 800-1200°C. Various synthetic gels are chosen as starting materials filled in Au-capsules and kept in a multi-anvil Walker-type apparatus at constant conditions for several hours or days. After each experiment the materials are studied using an electron microprobe and a scanning electron microscope.

First experimental results are partially consistent with preliminary calculations. Especially the formation of K-hollandite at pressures above 10 GPa appears the be confirmed in these experiments. In addition, the composition of micas becomes more magnesium-rich with increasing pressure and consequently the appearance of dark mica is common at higher pressures as well as a majoritic component in garnet.

**Talk**

## Slab-derived supercritical fluids: trace-element evolution and diagnostic fractionations

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During deep subduction, the slab can release supercritical fluids at P-T conditions higher that the second critical end-point of the system, i.e. at P-T conditions and geothermal gradients distinct from a lithology to another. These fluids have physical-chemical properties intermediate between an aqueous fluids and a hydrous-silicate melt, and their alkali-aluminosilicate solute load is expected to increase dramatically even for small increases of temperatures. **Experiments indicates that supercritical fluids are extremely enriched in LILE, LREE ± Sr ± HFSE**. While some authors argue that there is not significant differences on trace-element transport between supercritical fluids and hydrous-silicate melts, others suggest that supercritical fluids have higher capacity than a melt to mobilize LREE. These contrasting opinions are in part stoked by the permanent uncertainty to have actually reached supercritical conditions during experiments. However, although the efficacy of supercritical fluids in trace-element transport has been demonstrated, their trace-element fractionations and the related genetic processes are still poorly investigated. Moreover, while trace-element fractionations of aqueous fluids (e.g., high Ba/Th, Ba/La, U/Th, low La/Sm) are clearly distinguishable from those of hydrous-silicate melts (e.g., high La/Sm, low Zr/Nb, Ba/Th), at present none diagnostic trace-element ratio has been identified to discriminate between hydrous-silicate melts and supercritical fluids.

Here, we report trace-element composition (***in situ* LA-ICPMS analyses**) of a natural supercritical fluid released from UHP prograde-to-peak conditions along an intermediate gradient from a meta-arenite. In particular, we analyzed multiphase-solid inclusions trapped in kyanite during UHP prograde-to-peak evolution (700-860°C and 3.0-4.0 GPa) of a kyanite-bearing quartzite from Sulu (China).

This study allows: i) to characterize the evolution of trace-element concentration and fractionation in an evolving supercritical fluid released **by terrigenous sediments** along an intermediate gradient; ii) to define the role of progressive rock dissolution in trace-element release into the fluid; iii) to define the metasomatic efficiency of a supercritical fluid with respect to a hydrous-silicate melt; iv) to propose diagnostic trace-element ratios able to distinguish supercritical fluids from hydrous-silicate melts. These results have implications for characterization of slab-derived components in both natural and experimental samples.

Talk

## Macroscopic globules in glasses from the Izu-Bonin-Mariana fore-arc as a record of silicate melt-fluid exsolution during subduction initiation

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The Izu-Bonin-Mariana volcanic arc comprises a complete record from subduction zone initiation (52 Ma) to the formation of a mature intra-oceanic arc (<47 Ma). The International Ocean Discovery Program (IODP) Expedition 352 obtained samples via drilling of the fore-arc-basalt stratigraphy, which exhibit macroscopic globular textures in fresh andesitic glasses. However, it is unclear how these globules have formed, and whether they potentially represent fluid-melt exsolution textures. Such textures are assumed to result when water-saturated magmas reach oversaturation in a fluid phase during their ascent, and could indicate fluid involvement during subduction initiation.

Here we show, based on textural, major and trace element, and B, Sr isotope analysis, that the glassy matrix and globules are likely conjugated immiscibility partners. In this context, the glassy matrix represents the former silicate melt and the globules represent the remnants of the hydrous fluid. The exsolution process of the two immiscible liquids both lead to a close-to-spherical shape of the globules, but also triggered isothermal spherulitic crystallization induced by hydrous fluid loss. The hydrous fluid separated from its “solute” and its extraction from the system resulted in the formation of an interfacial textural unit, which surrounds the globules. The fluid exsolution process fractionated the fluid-mobile elements K, Tl, B, Rb, Li and Cs, and leads to a fractionation in B isotopes between the fluid and silicate melt of ca. 7‰.

The results of this study emphasize that a magmatic fluid is involved during subduction initiation in the Izu-Bonin fore-arc, which was either released from the hydrous fore-arc melt, or formed as the result of the assimilation of altered oceanic crust. Moreover, given that there is significant trace element fractionation and stable isotope fractionation as a result of fluid exsolution from an andesitic melt, this process needs to be taken into account in subsequent studies dealing with water-saturated subduction zone magmas.

Talk

## Syntectonic serpentinite dehydration within subduction zones

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At subduction zones seawater-altered oceanic lithosphere is returned to the Earth’s mantle, where increasing temperatures and pressures result in the progressive destabilization of hydrous minerals releasing aqueous fluids. This cycling of volatiles is one of the most distinctive features of subduction zones and has fundamental consequences for Earth’s geodynamics as well as chemical cycles. Fluids released from the subducting slab trigger sub-arc mantle melting leading to explosive volcanism and induce petrophysical changes during dehydration that are thought to be a source of intermediate-depth seismicity. Previously, we have investigated fluid escape mechanisms during serpentinite dehydration in a largely undeformed part of the Erro-Tobbio unit, Italy [1]. This unit has been subducted to peak metamorphic conditions of 2.0–2.5 GPa and 550–600 ºC, resulting in antigorite+brucite breakdown to form olivine+$H_2O$. Here, we focus on those domains that have undergone *syntectonic* dehydration to determine (i) the impact of deformation on fluid escape and (ii) the overall rheological behaviour of a dehydrating serpentinite system. To approach these issues we combine hyperspectral Raman imaging (HRI) with multi-scale electron microscopy encompassing backscattered electron mapping, electron backscatter diffraction, focused ion beam scanning electron microscopy and transmission electron microscopy. Crystal orientation mapping revealed that the antigorite is characterised by a crystallographic preferred orientation (CPO), whereas the metamorphic olivine lacks CPO. HRI of the deformation bands shows that nearly all olivine grains are surrounded by a prograde, hydrous phyllosilicate phase that is different to the original antigorite. In addition, these shear bands do not exhibit signs of instantaneous dehydration embrittlement. Based on these first results we discuss the rheology of a dehydrating serpentinite system.

**References:** [1] Plümper, John, Podladchikov, Vrijmoed & Scambelluri (2017), *Nature Geoscience* 10(2), 150-156.

Talk

## Melting of felsic continental crust at mantle depth: experimental constraints and implications for ultrapotassic magmatism

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Potassium-rich, mantle-derived magmatism occurs above active subduction zones and in post-collisional settings. Potassic–ultrapotassic magmas combine high concentrations of mantle-compatible elements with continental crust-like isotopic signatures and trace element patterns. These characteristics are indicative for the contribution of high amounts of subducted continental material to their source regions. During oceanic closure, continental crust may become subducted and liquids released from it could represent suitable metasomatic agents to generate hybrid mantle domains. To test this possibility, we explored the major and trace element composition of partial melts from felsic crust at 2.0 to 4.5 GPa and 675 to 900°C. Water-present experiments on a slightly peraluminous metagranite from the Dora Maira Massif, Western Alps produced a paragenesis of coesite/quartz–phengite–clinopyroxene±K-feldspar/K-cymrite±garnet coexisting with a hydrous silicate melt at run conditions. The silica-rich melts are highly alkaline with high K/Na ratios due to the compatibility of Na in clinopyroxene. Alkalinity increases with increasing pressure and melt compositions become peralkaline above 2 GPa. Accessory phases (allanite, monazite, apatite and zircon) may play a key role in controlling the trace element patterns of coexisting liquids. Although the strong alkalinity enhances accessory phase solubility, allanite controls the LREE–Th budget and causes high Th/La of up to ~2 in coexisting melts. High Th/La ratios are typical features of orogenic ultrapotassic rocks, such as the lamproites of the Alpine–Himalayan belt, for instance. This work shows that ultra-high pressure partial melts from felsic crust have many geochemical features closely matching those of (ultra)potassic rocks.

Talk

## Fluid-driven transformation of glaucophanite to an omphacite-vein assemblage under near peak conditions in the continental crust, Mt. Emilius, Italian Western Alps

**Sebastian Weber**

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Inside the ultrahigh-pressure ophiolite complex of the Penninic Alps a series of continental basement slices is inserted in an intra-ophiolitic position along the tectonic boundary between two major Penninic nappes. Being the most prominent member of this series, the Mount Emilius provides an exceptional possibility to study omphacite bearing mineral-vein assemblages. These are seperated by a transition zone from a surrounding omphacite-free glaucophanite. Petrographic and field observations as well as whole-rock compositions suggest that within the Mount Emilius, eclogite facies reaction products form only where Ca-metasomatism induces a change in whole rock composition of the precursor glaucophanite host. These substantial differences in bulk rock composition demonstrate how spatially limited eclogitization is controlled by chemical redistribution, the degree of fabric evolution and associated metamorphic reactions along fluid transport pathways. Thermodynamic modelling of selected bulk rock compositions of both glaucophanites and omphacite-vein assemblages confirms their coexistence near peak metamorphic conditions of 1.9 ± 0.1 GPa and 550 ± 50 °C. These constraints are consistent with thin section observations that none of the studied samples contain coesite relicts. Given the structural position of the Mt. Emilius klippe, the critical question arising from these results is how much of this unit has actually "travelled the ultra-high pressure route" of the underlying Zermatt-Saas Zone, and how much of it was never buried to pressures greater than 2.0 GPa.

# Topic 17: Open Session

## 17a) Young Scientist Session

Poster

### Chemostratigraphic study on the Upper Cretaceous-Paleogene sedimentary sequence in Wassief area, Safaga, Egypt

**Rania Abu-Ali**, **Ahmed El-Kammar**

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Chemostratigraphic study on the Late Cretaceous-Paleogene sedimentary sequence of Wassief borehole, near Safaga on the Red Sea area of Egypt was achieved. Based on the biostratigraphic investigations on core samples, eight biozones and three hiati were identified. Petrographically, the study samples can be subdivided into three main lithofacies, namely; (1) phosphorite; (2) carbonate; and (3) shale. Mixing of two, or even the three, lithofacies at different proportions is quite reasonable. Mineralogically, the X-ray diffraction (XRD) analysis revealed that the main identified clay minerals are kaolinite and smectite-illite mixed layers. The marked dominance of kaolinite at the Late Cretaceous-Paleogene boundary proposes rainy climatic conditions. On the other hand, the dominance of smectite-illite mixed layers in the Paleocene sediments reflects a warm and seasonally humid to arid climate. The identification of the non-clay minerals completed by microscopic examination supported by XRD and Raman spectroscopy. Statistically, five groups of geochemical controlling factors are recognized, namely; terrestrial/marine, phosphorite, redox potential, carbonates, and titanium factors. The obtained biostratigraphical, mineralogical and geochemical results are integrated in a high-resolution chemostratigraphic zonation of the Upper Cretaceous-Paleogene sedimentary sequence under consideration.

Poster

### Numerical modelling of salt-related stress decoupling in the North German Basin

**Steffen Ahlers**, **Tobias Hergert, Andreas Henk**

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Data from the North German Basin (NGB) shows different orientations of the maximum horizontal stress $S_{Hmax}$ depending on the position relative to the Zechstein salt layer. The stress pattern in the subsalt region (below the salt) is rather uniform and consistent to the regional stress field, whereas stress orientations in the suprasalt part (above the salt) are variable, most likely reflecting local conditions. The contrasting orientations are thought to be related to stress decoupling at the salt layer between the sub- and suprasalt sections. The aim of this numerical modelling study is to evaluate factors controlling the stress fields below and above the Zechstein layer and to estimate the role of material parameters influencing the decoupling effect of the salt such as the dynamic viscosity.

Based on the geological setting of the NGB a strongly simplified finite element model consisting of three layers, representing the subsalt, salt and suprasalt sections, is set up. Thereby the geometry of the salt layer is that of a diapir. The total thickness of the model is 10 km and the area is 80 x 80 km. To simulate the regional stress pattern shortening is applied to the subsalt section. A range of values for the dynamic viscosity of the salt ($10^{18}$ to $10^{24}$ Pa s) and different shapes of the salt diapir are considered to assess the influence on the stress field.

The results of our numerical study support the view that the subsalt part of the NGB is mainly influenced by the far-field stress field, whereas the suprasalt section has an independent stress orientation that can be influenced by local structures like salt diapirs. Depending on distance to the top of the salt diapir the direction of $S_{Hmax}$ is changing within the suprasalt sediments from a parallel to a radial pattern. These distances are changing for different diapir sizes. In addition to orientation the gradients and magnitudes of the differential stress ($S_{diff}$) also show differences between the subsalt and suprasalt sections. Furthermore, complete stress decoupling between the sub and suprasalt is found for all salt viscosities below $10^{20}$ Pa s.

Poster

## Relationship between sediment facies and stable isotopes within a lacustrine sequence of mid-Miocene age in SE Kazakhstan

**Josephine Louise Iris Arndt, Konstantin Frisch, Silke Voigt**

*Uni Frankfurt, Germany*

Western Central Asia experienced a phase of widespread lake formation during the mid-Miocene, exemplified by a 370-m long succession of lacustrine carbonates in the Aktau mountains, Ili Basin, SE Kazakhstan. The development of this lacustrine system is of special interest since it indicates a period of enhanced water supply in a time of general aridification. Here we studied the stable isotopic composition (carbon and oxygen) of carbonates to understand their relationship to the sediment facies and to gain insights into the paleoenvironmental history of the succession. The facies classification bases on outcrop lithology and sediment mineralogy investigated in thin-sections. The succession exposes a development from a dry mudflat towards a playa environment and later towards a freshwater lake with superimposed short-term water level fluctuations. The corresponding stable isotope record displays strong variations with values ranging between -12 and -1 ‰ for carbon, and -12 and +2 ‰ for oxygen, respectively. The carbon isotopic composition reflects variable contributions of pedogenic and lacustrine carbonates, while the oxygen isotopic composition represents the composition of meteoric, ground and lake waters. Further, the oxygen isotopic composition serves as a measure for the ration of aquifer recharge and net-evapotranspiration. Both parameters respond sensitive to evaporative enrichment and lake water salinization. The long-term evolution of stable isotopes closely resembles evolution of the successive facies associations (dry mudflat, subaerial playa, playa lake, deep perennial lake and shallow proximal lake). Furthermore, it exposes prominent excursions associated to distinct marker horizons (MH1-6). MH3 represents maximum lake water salinity evident from the stability of anhydrite and the most positive oxygen isotope values, and thus the highest degree of aridity in the region. Another horizon, MH4, represents complete lake desiccation manifested by the progressive rise of both, carbon and oxygen isotopes. MH5, instead, displays prominent negative stable isotope shifts in a period of soil formation, meteoric infiltration and enhanced siliciclastic input. The perennial lake between MH4 and MH5 reflects increased water supply likely because of climate cooling (Miocene climate transition) and the north and eastwards expansion of the Eastern Paratethys. In general, the Aktau succession displays a rather regional feedback of Central Asia's aridification with elevated rates of water accumulation northwest of the orographic barrier of the juvenile Tian Shan Mountains.

Poster

## Tectonics shaping the landscape of Southern Montenegro and Northern Albania: A multidisciplinary study of Holocene surface processes at the Dinarides-Hellenides transition.

**Rosalie Kremser[1], Leah Freudenberg[1], Philip Korsten[1], Peter Biermanns[1], Benjamin Schmitz[2], Klaus Reicherter[1]**

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Montenegro and Albania are recognized as one of the tectonically and seismically most active areas in Europe. Continental subduction of the Adriatic microplate below the Eurasian plate is expressed in ongoing fold-and-thrust belt development in the Dinarides-Hellenides, a southern extension of the Alps. Our work contributes to an interdisciplinary study, aiming to quantify the effect of neotectonic deformation on dynamic landscape development in the Dinarides-Hellenides transition. Particularly, we localize and estimate locally constrained uplift and subsidence interacting with fluvial processes and sea level change, and distinguish compressionally and extensionally formed structures. The first part of our study includes detailed mapping and sampling of normal fault scarps in Southern Montenegro that fall into an area intrinsically dominated by compressional tectonics. Geometry and spatial orientation of fault planes, properties of fault plane surfaces (e.g. multicoloured, probably earthquake-related ribbons and roughness variations derived from T-Lidar scanning and macroscopic observations) as well as uniform displacement vectors suggest a tectonic origin of the fault scarps and post-LGM annual slip rates of c. 0.3. - 0.4 ± 0.05 mm. The second method is the extraction of shallow drill cores from the coastal plains of Albania and Montenegro, targeting a reconstruction of depositional conditions and development of the Adriatic coastal area. Sediment cores are analyzed by XRF, magnetic susceptibility, sieve analysis and characterization of fossils. Results suggest a change from marine to terrestrial conditions during the Holocene although global sea level has been constantly rising during this period. We propose that overall uplift of the Adriatic coastal area combined with dynamic changes in fluvial deposition are responsible. Both approaches show the existence of active tectonics in the area, significantly shaping the local geomorphology.

Poster

## Electrical Resistivity Tomography of the Lichtenstein cave system (Harz, Germany)

**Rouven Benedikt Brune**, Paul Berndt, Dennis Flenner, Johanna Pavlak

*University of Bremen, Germany*

The gypsum karst region in the southern Harz area near Osterode is due to its constant damp climate prone to karst formation which started to evolve in the Upper Pleistocene and is still an ongoing process. The whole Harz region offers stunning cave systems but just a few of them are suitable for geoelectrical exploration. The Lichtenstein cave has been discovered in the early 1970s and bears valuable archaeological human remains from the bronze age.

Speleologist explored it in the upcoming years after the discovery and estimated that the whole system is stretching over a length of 115 m. Unfortunately, it's protected under nature conservation since 1981 and therefore inaccessible for further studies. Up to this point it is expected that the actual cave system is greater than the known expansion.

Our approach is it to map the Lichtenstein cave with a non-inversive geophysical method on the base of not harming protected animal life inside the cave. We use the geoelectrical mapping method in a rectangular grid around the expected cave area to perform an electrical resistivity tomography. The acquired data is later used to develop a 3D inversion model with the software package R3t from the Lancaster University.

Talk

## Synecological studies of the Lower Devonian Hunsrück Slate Fauna

**Roman Luca de Giorgi**, Jes Rust

*University of Bonn, Germany*

Understanding an ecosystem, the correlation between organisms and their respective environmental surroundings as well as their ecological interrelationships are a key focus of palaeobiological research, often strengthened by comparison with recent habitats providing a similar or, at least, comparable setting.

With over 260 described animal species, the archives of the fossil material gathered from the Lower Devonian Hunsrück area (southern Rhenish Massif) provide a vast amount of material showing excellent states of preservation due to pyritization and even conservation of soft tissue. Apart from the actual slate material collected from the quarries near Bundenbach, the focus in this research was set on the x-ray archives from W. M. Lehmann, W. Stürmer and W. Blind, especially on slides with several different organisms accompanied on a single slide. The co-occurrences were statistically evaluated and repeating patterns in the faunal composition were mainly interpreted by focusing on the feeding behavior and diet of the organisms, stating possible predator/prey relationships and symbiosis. And even for now extinct species like *Mimetaster hexagonalis* or *Vachonisia rogeri*, the comparison with recent organisms leads to highly reliable conclusions in their ecology. After the statistical analysis, the six localities around Bundenbach, from where the investigated material has been collected, were correlated in an overall environmental setting.

To bring this into an even broader context, further research is planned to focus on material from the Lower Devonian of the Ardennes (Belgien, Luxembourg, France) in order to reconstruct the whole former Rhenohercynian depositional environment.

Poster

## Geological Investigations on a suspected Fault Line in the north-western Vogelsberg Region by means of Core Drilling

**Tino Degenhardt**[1], Alexandra Fischer[2], Michael Trinkler[3], Wolfgang Schiller[1], Peter Prinz-Grimm[1]

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The Vogelsberg, the biggest contiguous surficial volcanic area in Middle Europe, exhibits interesting complex geological formations and has therefore been investigated frequently since the past century. Through its north-western part, a new highway is planned by the German government. Since January 2017, many drills are made with high spatial resolution providing a great opportunity to improve our scientific understanding of this part of the Vogelsberg area and its potential fault zones.

Thus, using this convenient occasion, an evaluation of a suspected fault line near Homberg (Ohm) is an expedient and promising work for a Bachelor thesis. By using more than 40 cores, along a line of approximately one kilometer length crossing the potential fault zone a synopsis of vertical drill profiles has been designed. The presented study does not confirm the presence of the suspected fault as originally expected, but it rather shows a complex structure of several faults due to raising and sinking processes in the past. Hints for the existence of the fault in the explored area are given by a large number of sheared stones, many gaps filled with clay and a change of the main basalt type. On the other hand the are under investigation could possibly have experienced considerable sinking processes. The latter can cause small faults, which are widely spreaded rather than representing a visible sharp geologic boundary.

Poster

## Osteological description of plateosaur remains from the Keuper of Thuringia

**Effi-Laura Drews**[1], **Jens Lallensack**[1], **P. Martin Sander**[1], **Oliver Wings**[2]

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*Plateosaurus* is one of the most abundant dinosaurs from the Triassic of Central Europe. It is commonly known from over 40 localities of Norian age from France, Switzerland, and Germany. The basal sauropodomoph is mostly found in fluvial mudstones of the Knollenmergel and Stubensandstein. Here we describe a pubis and a tibia from the Arnstadt formation of the Drei Gleichen region in Thuringia (Germany). The disarticulated pubis fragments were reassembled and both specimens were drawn for description. The preservation of the tibia is of particular interest, with only the natural cast of the medullary cavity remaining. We compared the specimen with a 3D model of the medullary cavity of the *Plateosaurus* specimen GPIT 1 from Trossingen. Showing a considerable amount of similarities and due to the fact of *Plateosaurus* being the only animal of this size during the Norian, we hypothesise the natural cast to belong to a plateosaurid. We report the first example of natural cast preservation in plateosaurids. The description of the remains makes the Drei Gleichen region the second locality for *Plateosaurus* remains in Thuringia. Further studies need to clarify the mode of preservation of the tibia in context to the bone preservation of the pubis.

Talk

## Early evolution and palaeobiology of pygmy grasshoppers (Orthoptera: Tetrigidae) with the description of new genera and species

**Christine Gabriele Grabatin**[1], **Jes Rust**[1], **Jan Audun Rasmussen**[2], **Henrik Madsen**[2]

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With 280 genera and more than 1,900 described species, Tetrigidae is a highly diverse group within the Caelifera. Regardless of this, scientific attention regarding alpha taxonomy, evolution, biology as well as ecology is still limited, resulting in uncertainties concerning their phylogenetic position, as well as species descriptions and the interpretation of morphological characters.

Even though being an ancient family within the Caelifera, Tetrigidae show a very scant fossil record of only seven species being described, and with none being older than the Early Eocene, very little is known about their early evolution. Previously, the Early Cretaceous taxa *Archaeotetrix locustopseiformis* Sharov, 1968 and *Prototetrix reductus* Sharov, 1968 were regarded as the oldest species assigned to Tetrigidae. In our opinion, however, the assignment is in lack of convincing evidence, and they should be excluded from this family.

The Crato Formation (Brazil), being the only Gondwanan, non-marine conservation Lagerstätte of Aptian/Albian age poses unusual insights into early insect evolution. A new genus and species of a probable stem lineage representative of the Tetrigoidea is described from a well-preserved, complete male specimen, even this single specimen does not provide enough data for a safe systematic assignment. Several characters indicating a relationship to the Tetrigidae, others, however, clearly contradictory, suggesting an earlier evolutionary state before the divergence of Tridactylidea and Acrididea in the late Palaeozoic.

The Stolleklint Clay and the Fur Formation in Denmark yield large amounts of well-preserved fossils ranging from the Upper Paleocene to the Lower Eocene. From these offshore sediments 433 specimens of Tetrigidae have been recovered and described. The exceptional preservation allows to interpret even delicate morphological structures with regard to their function, biology, and behaviour. From these specimens a new genus with three new species has been described. The close morphological resemblance to recent Tetrigidae shows an advanced evolutionary state already in the Early Eocene. Furthermore, the occurrence of Tetrigidae in a completely marine setting, as well as the ratio of males and females and the consistently long hind wings lead to the conclusion that the assemblage represents former dispersal flights after mating.

Talk

## Foraminifera rocket experiment - Biomineralization research in space: Limits and challenges

**Katrin Hättig**[1], **Greta Sondej**[1], **Christoph Kulmann**[1], **Scarlett Gac Caceres**[1], **Jan Blumenkamp**[1], **Nils Kunst**[1], **Johanna Hartmann**[1,2], **Niklas Kipry**[1], **Kay Menken-Siemers**[1], **Daniel Rippberger**[1]

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Biominerals have been of interest as materials since humanity's earliest days of utilizing shell and bone to create tools. Their high-performance properties compared to inorganic minerals and synthetic composites keep scientific interest high and much research effort is directed towards an understanding what controls the biomineralisation process and how morphogenesis is regulated. Aim of our project is to investigate how microgravity affects biomineralization in *Amphistegina lobifera,* a tropical Indo- Pacific endosymbiont bearing calcifying benthic foraminifera species. Our experiment FORAREX is part of the REXUS/BEXUS program, which is an opportunity for students to carry out scientific and technological experiments on board of a sounding rocket. Our assumption is that under long-term microgravity, both the microscopic and ultrastructure of foraminiferal tests will differ from earth-bound growth patterns.

On the REXUS mission the response of Foraminifera to physical stress during rocket launch, e.g. vibration and acceleration will be tested. Our life-support system cultivating foraminifera will be tested for general mission approval. During a later flight stage when microgravity sets in, its influence on the calcification and motility behaviour of foraminifera will be the focus of investigation. We will investigate how microgravity affects growth and biomineralization rate, crystal properties and morphogenesis.

Investigations will be conducted using a miniaturized container with a flow cell examination chamber and a closed-circuit life support system with integrated LED-based illumination to support photosynthesis. The Foraminifera will be observed using a camera. Temperature, O2 and pH will be recorded using high-performance miniaturized sensors. We also test cell survival during the physical stresses involved during launch and flight and the stability of our life-support system during the mission.

Goal of the current REXUS experiment is to optimize the setup for a future long-term experiment on board of the International Space Station (ISS), where we would like to investigate foraminiferal test formation under extended microgravity influence. Therefore, it is a precondition to intensively test the experimental set-up and its performance during the rocket flight. We will present the current experimental setup with first results on growth under closed-system cultivation conditions.

**Poster**

## Reconstruction of the Nusplingen Plattenkalk paleoenvironment with fossil shark-teeth geochemistry

**Katrin Hättig[1,2], Kevin Stevens[1], Detlev Thies[3], Günter Schweigert[4], Jörg Mutterlose[1]**

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Shark teeth are composed of bioapatite and can be used as an archive for paleoseawater temperature reconstructions. Unaltered phosphate stable oxygen isotope composition ($\delta^{18}O_{(PO4)}$) reflects the temperature at the time of apatite formation in marine vertebrates. Apatite has been considered to be more robust to diagenetic alteration than calcite since apatite is less prone to dissolution and recrystallization processes during diagenesis. Shark teeth are formed and replaced rapidly, their biomineralization takes days to weeks. They are therefore providing short-term signals of the isotopic composition and temperature of the ambient water in which the teeth were mineralized.

Shark teeth are composed of two main mineralized tissues, enameloid and dentin. Enameloid is composed of the diagenetically stable fluorapatite. The mineral phase of dentin on the other hand consists of hydroxylapatite, which is more likely to be affected by diagenetic processes. During diagenesis hydroxylapatite recrystallizes to fluorapatite. We studied the diagenesis and stable oxygen isotope composition of 6 fossil shark teeth (*Sphenodus nitidus*) from the Nusplingen Plattenkalk (upper Kimmeridgian, Upper Jurassic) of southwestern Germany. Enameloid and dentin were measured separately and compared to co-occuring $\delta^{18}O$ data of belemnite rostra and carbonate sediments from the same locality to evaluate effects of diagenesis and the potential of this data for paleoenvironmental reconstructions. The chemical composition of the enameloid did not change significantly during diagenesis. Fluorine, $Mn^{2+}$ and$REE^{3+}$ incorporation, as well as sediment filled or cemented pores and fractures have been observed in the dentin. The $\delta^{18}O$ values of the dentin show an offset of up to 1.85‰ compared to the enameloid values. Interpretation of the dentin data in terms of paleotemperatures would lead to an overestimation of the temperatures by 6-9°C of teeth. Paleotemperatures calculated from the enameloid are similar to belemnite data and indicate a pelagic habitat of both groups. This study shows that dentin and enameloid should be analyzed separately for geochemical analysis. The data obtained provide new insights into the ecology of the late Jurassic Nusplingen lagoon.

**Poster**

## Lifespan of water reservoirs estimated from cosmogenic 10Be in stream sediment – A case study from Western Turkey

**Caroline Heineke[1], Ralf Hetzel[1], Cüneyt Akal[2], Marcus Christl[3]**

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The retention capacity of water reservoirs is generally impaired by upstream erosion and reservoir sedimentation, making a reliable assessment of erosion indispensable to estimate reservoir lifetimes. Widely used river gauging methods may underestimate sediment yield, because they often integrate over short time periods, not recording rare, high-magnitude erosion events, and may underestimate bedload transport. Hence, reservoir lifetimes calculated from short-term erosion rates should be regarded as maximum values. We propose that erosion rates from cosmogenic $^{10}Be$, which commonly integrate over hundreds to thousands of years, are useful to complement short-term sediment yield estimates and should be employed to estimate minimum reservoir lifetimes. Here we present $^{10}Be$ erosion rates for the drainage basins of six water reservoirs in Western Turkey, which are located in a tectonically active region with easily erodible bedrock. Our $^{10}Be$ erosion rates for these catchments are high, ranging from ~170 to ~1040 t/km$^2$/yr. When linked to reservoir volumes, they yield minimum reservoir lifetimes between 25±5 and 1650±360 years until complete filling, with four reservoirs having minimum lifespans of <110 years. In a neighboring region with more resistant bedrock and less tectonic activity, we obtain much lower catchment-wide $^{10}Be$ erosion rates of ~33 to ~95 t/km$^2$/yr, illustrating that differences in lithology and tectonic boundary conditions can cause substantial variations in erosion even at a spatial scale of only ~50 km. We suggest that short-term sediment yield estimates and $^{10}Be$ erosion rates should be employed in concert to predict the lifetimes of water reservoirs.

Talk

## Dynamic Mineral Recrystallization – Unlocking critical metals from deep-sea ferromanganese nodules and crusts

**Tobias Hens, Joël Brugger, Andrew Frierdich**

*Monash University, Australia*

Deep-sea ferromanganese nodules and crusts attract the attention of an emerging deep-sea mining industry due to their unusual enrichment of critical metals, which are increasingly used in a wide variety of high-tech and green-tech applications. Metal recovery and processing of these deposits will be cost-intensive and require innovative solutions. The development of sustainable and tailored metallurgical processes thus represents one critical component that will positively affect the marine mining value chain.

Dynamic mineral recrystallization (DMR) may have notable potential for future hydrometallurgical applications. DMR occurs as a background process during biogeochemical manganese (Mn) cycling when dissolved Mn(II) is in direct contact with Mn oxides. Metals such as nickel (Ni), which are incorporated in the Mn oxide host phases, are cycled between solid phase and solution through coupled dissolution (trace metal release) – reprecipitation (trace metal incorporation) mechanisms.

We recently demonstrated that Ni is effectively released into solution, surface-(re)adsorbed, and progressively incorporated during synthetic manganite recrystallization, with up to 40% of Ni incorporation into the Mn oxide structure being observed over time (Hens et al., 2018). Based on these results we employed similar techniques to investigate the impact of DMR on deep-sea ferromanganese nodules and crusts. A suite of geochemical analyses was used to characterize the bulk geochemical and structural composition of the samples. Ni exchange experiments with a $^{62}$Ni stable isotope tracer were subsequently conducted to quantify the amount of Ni that participates in mineral-fluid cycling. Furthermore, the effects of $Mn(II)_{aq}$ concentration, and additional variables, such as $Fe(II)_{aq}$, pH, and time were evaluated.

Our results show that, although Ni experiences mineral-fluid repartitioning in $Mn(II)_{aq}$-free suspensions, increased $Mn(II)_{aq}$ concentrations effectively catalyze Ni exchange between solid phase and solution over time. Ni exchange of more than 20% was observed in samples with high solid-associated Fe concentrations during reactions in pH 7.5 suspensions. We thus hypothesize that DMR (a) has direct implications for the genesis, alteration, and trace metal enrichment of deep-sea ferromanganese nodules and crusts and (b) may also represent a cornerstone for the development of tailored, sustainable, and eco-friendly hydrometallurgical metal extraction techniques.

**Key words:** Ferromanganese Nodules, Polymetallic Crusts, Dynamic Mineral Recrystallization, Hydrometallurgy, Nickel Isotope Tracer

**References:**

Hens, T., Brugger, J., Cumberland, S. A., Etschmann, B., Frierdich, A. J., (2018), Recrystallization of Manganite (γ-MnOOH) and Implications for Trace Element Cycling, *Environmental Science & Technology*, *52* (3), 1311-1319, DOI: 10.1021/acs.est.7b05710

Talk

## Sources of the Saharan dust in Greece

**Marcjanna Jędrych[1,2], Barbara Woronko[1], Dorota Chmielowska[3], Irena Tsermegas[2]**

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The number of Saharan dust events in Northern Africa is raising gradually, as a consequence of enhanced desertification, human activity and climate change. An annual dust transport towards Europe is estimated for about 120 million tons. As it has profound impact on both environment and human's health it is crucial to determine its features what may also lead to their source areas identification and for the understanding of dust atmospheric processes.

The case study focused on characteristics of the three samples of Saharan dust from Greece. The first one was collected on 21$^{th}$ of March, 2016 in Athens, and the others – 22$^{th}$ of March, 2018 on Crete and Santorini. Mineralogy, microtexture of quartz silt fraction, roundness and granulometry of each sample were analysed. The meteorological situation during mentioned storms and in the antecedent period was investigated as a background.

The samples differed in the colour: Athens and Santorini – grey, and Creta – brown. According to grain size analysis, 86% of dust grains collected in Crete and 80% in Santorini was classified as silt and just 13.4% and 19.8% as fine sand, whereas just 65.5% grains from Athens tended to be fine silt and 34% - fine sand.

Analysis performed with SEM BSE use enabled us to determine the grain microtextures and with morphology G3 apparatuses the shape of grains in fraction 20-40 μm. Obtained results showed that in the sample from Athens almost half of them was angular with sharp edges and corners and most of them were overgrowth quartz, whilst in terms of the dust from Crete more than 50% of grains was subrounded or rounded which surfaces were intensive eaching with adhering particles consisted of amorphous precipitation, while the quartz grains from Athens had rather fresh surfaces. Moreover grains form Santorini have irregular shape and most of them are feldspars (ca. 90%), ca 5-7% there are dolomite and fragments of carbonated rocks. Quartz grains represent a percentage less than 2-3% of all silt size grains.

Performed researches indicate that the dust sample collected on Crete were transported from farther source area than the dust gathered in Athens. We suggest the dust source area in the first case is located in the Central Sahara, and in the second – in the Nile delta. The source of dust in Santorini is enigma at this moment because according to mineralogical composition they represent volcanic rocks composed mainly of feldspars.

**Talk & Poster**

## Modelling the transport behaviour of contaminants potentially released by decommissioning wastes deposited on generic landfills to the groundwater, using the transport code SPRING

**Marc Johnen[1], Holger Seher[2], Torben Weyand[2], Andreas Artmann[2]**

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In Germany, all power and nearly all research reactors will be shut down by the end of 2022. Also, a large number of nuclear facilities are at different stages of decommissioning. The majority of the decommissioning and dismantling wastes of nuclear facilities is not or just slightly contaminated. These volumes must pass an officially approved clearance or issuing procedure for recycling or reuse, which is regulated in the Radiation Protection Ordinance (StlrSchV) [1]. After approval, these volumes are fed into the material cycle or professionally disposed of. According to the StrlSchV, only landfills of classes DK I to DK IV (DK, *Deponieklasse* in German) of the German Landfill Ordinance (DepV) [2] have the permission to deposit the decommissioning waste.

Numerical models of generic landfills of DK I to DK III with deposited decommissioning wastes are used to estimate the potential release of radionuclides. In our previous work [3] and [4], we used 1D and 2D models to estimate the release. In this study, the model domain is extended to represent generic landfills in 3D with an associated aquifer. All simulations are performed with the transport code SPRING [5].

The geometric structure and parameterisation of the landfills are given by DepV and assumptions by other generic scenarios for the landfill disposal paths. In line with the deposition of waste on a real landfill, the partial placement of waste into the landfill and a resulting increase in deposited waste with time is considered as a start for the simulations instead of a directly sealed landfill. Multiple simulations are used to determine the retention and transport behaviour of the radionuclides, dependent on the landfill classes. The transport is influenced by advection, dispersion, diffusion, sorption and radioactive decay. The results show the sensitivity of the transport parameters relative to the radionuclide concentration in the groundwater downstream of the landfill.

[1] Strahlenschutzverordnung (StrlSchV) (BGBl. I 2016).

[2] Deponieverordnung (DepV) (BGBl. I 2016 S. 382).

[3] Artmann, A., et al. (2014): GRS-342, ISBN 978-3-944161-22-8.

[4] Seher, H., et al. (2016): DOI: 10.1016/j.pnucene.2016.01.015.

[5] König, C. M., et al. (2017): SPRING, Benutzerhandbuch für Version 4.32.

**Talk**

## Raman spectroscopy as a tool for determining the chemical composition of plagioclase minerals

**Matthias Krug[1,2], Burkhard Schmidt[1]**

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Being the most abundant mineral in the Earth’s crust, plagioclase is present in a large variety of rocks. Especially for magmatic rocks, the chemical composition of plagioclase in terms of anorthite and albite content is of high importance for the determination of the differentiation grade, the melting temperature and for the classification of the rock itself. However, a quantitative analysis of major minerals, such as plagioclase, is time consuming due to necessary preparation prior to the analysis. Here we present a method to determine the proportions of anorthite and albite by using Raman spectroscopy, which requires less preparation effort. For this, we synthesized high-temperature plagioclases between pure albite and pure anorthite by crystallising plagioclase glasses under sub-solidus conditions and measured the composition by elctron microprobe analysis. With Raman spectroscopy we found a clear correlation between Raman shift and chemical composition. The Raman bands at 478 - 488 cm-1 (here called band D) and 558 - 577 cm-1 (here called band F) show the best correlations. As both bands show opposing trends with increasing anorthite content, their difference in position (ΔFD = Raman shift band F – Raman shift band D) is most suitable for the determination of composition. However, the comparison of the obtained correlation to that to natural plagioclase samples from mostly volcanic rocks indicates a systematic deviation (up to 10 mole%) from the synthetic samples. This disagreement is probably related to some structural differences between synthetic and natural plagioclases. With the data of the natural samples we created a new correlation, which is An% = 0.0374 * |ΔFD|2 - 9.8526 * |ΔFD| + 612.6, where An% is the anorthite content of the sample in mole% and ΔFD is the difference in Raman shift of bands F and D in cm-1. With this correlation natural high-temperature plagioclases can rapidly and easily be characterized quantitatively with an accuracy of ± 5.75 mole% (2σ) without need for any sample preparation.

Poster

## Chaos of the Solar System: A method to detect chaotic transitions in Geological Time Series

**Melanie Reinelt**[1], **Pälike Heiko**[2]

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Climate changes in Earth's history were induced by cyclic variations of insolation received on Earth. These variations were triggered by quasi-periodic changes in the Earth's orbit. Detected astronomically driven cycles – Milankovitch cycles - recorded in sediments are used to generate age models of high accuracy. These age models are adjusted to astronomical solutions, which are based on the numerical integration of modern gravitational interactions in the Solar System. Due to the chaotic behaviour of the Solar System, the duration over which Earth's orbital variations can be computed with precision is limited. It is thus important to detect chaotic transitions in geological data, in order to verify and extend astronomical solutions (Laskar solutions). Chaotic transitions occur between the ratio change of two resonant astronomical frequencies of Mars' and Earth's orbit. It is necessary, to follow the evolution of eccentricity and obliquity amplitude modulation, which provide the "fingerprint" of these transitions. We developed a method with the help of two Laskar solutions: $La_{1993}$ (Laskar et al., 1993), which calculates a chaotic transition between 25 and 30 Ma, and $La_{2004}$ (Laskar et al., 2004) with a computed chaotic transition between 85 and 92 Ma. This method will be applied on datasets covering the Eocene, the Paleocene and part of the upper cretaceous.

Poster

## Geochemical characteristics of gabbroic rocks in the Gasht-Masuleh area, Alborz Mts.,north Iran

**Leila Rezaei**[1,2], **Martin J. Timmerman**[2], **Mohssen Moazzen**[1]

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As part of the Alpine-Himalayan orogen in north Iran, the E-W trending Alborz Mts. form the boundary between the Palaeo-Tethys suture zone and the Central Iran microplate. Subduction of the Palaeo-Tethys Ocean and later extension produced a variety of volcanic and plutonic rocks of varying ages In the Gasht-Masuleh area in the Alborz Mts. The parent melts of coarse-grained gabbros intruded Palaeozoic metasediments and Mesozoic sediments. Apart from local brittle faulting and tilting, the intrusions are not deformed and seem to represent a younger magmatic event. Petrographically, they can be divided into cumulates and isotropic gabbros, all mainly composed by varying proportions of olivine ± orthopyroxene + clinopyroxene + plagioclase + biotite. Clinopyroxene is the dominant cumulus mineral, while plagioclase is the intercumulus phase. Whole rock variation diagrams for MgO vs. $Al_2O_3$, $Na_2O$ + $K_2O$, $TiO_2$, CaO, Sc, Cr, Ni and Sr show simple, linear positive and negative mixing trends reflecting accumulation of clinopyroxene, olivine and plagioclase. Whole rock major and trace element compositions suggest generation of subalkaline parent melts of tholeiitic affinity in a subduction related (arc) setting, but a lithospheric extension-related origin cannot completely ruled out as indicated by the clinopyroxene compositions ($En_{41.0-49.8}$, $Fs_{0.9-12.7}$, $Wo_{41.2–51.7}$), which is supported by the wide range in plagioclase composition (andesine to bytownite, $An_{29.7-89.2}$). Chondrite normalized rare earth element plots show light REE enrichment ($(La/Yb)_N$ = 3.5 - 9.3) compared to heavy REE abundances ($(Dy/Yb)_N$= 1.4 - 1.8), which may point to relatively low degrees of mantle melting. Alternatively, Nb and Ti negative anomalies, elevated $(La/Sm)_N$ (1.20 to 2.66) and $(La/Yb)_N$ ratios (3.48 to 9.32), in combination with a negative correlation between Ba/La and $(La/Sm)_N$ can also be the result of contamination of the mafic parent melt with continental, arc-related crustal sediments and/or slab-derived fluids. Ongoing determinations of zircon U-Pb crystallization ages in combination with phlogopite Ar-Ar cooling ages will allow us to find out the temporal relation of the Gasht-Masuleh gabbroic rocks to the effects of Palaeo-Tethys or Neotethys Ocean subduction in Iran.

Poster

## Mapping of a duplex structure within the Middle Allochthon in the northern Fjällfjäll Window (N-Caledonides, N-Sweden )

**Nikita Skopincev**

*Martin-Luther-University Halle-Wittenberg, Institute of Geosciences and Geography, Germany*

The geology of the Scandinavian Caledonides is mainly affected by the Caledonian Orogeny, which resulted from the closure of the Iapetus ocean and Baltica's collision with Laurentia in the midlate Silurian. During this tectono-metamorphic deformation an orogenic wedge was obducted on the western edge of the Baltic Shield. The orogenic wedge was formed by the stacking of different lithological nappe units: the Lower, Middle, Upper and Uppermost Allochthon. The Middle Allochthon served as the base for the overthrusting of the Upper and Uppermost Allochthon. As a result of intense erosion tectonic windows were formed in which these nappe-complexes can be studied.

The following thesis covers the investigation of a 2,5 $km^2$ area in Västerbotten, North-Sweden. In the working area of the northern Fjällfjäll Window, the units of the Middle and Upper Allochthon are exposed in an antiformal duplex-structure. These have an arch-formed structure with alternating strike directions from NW to NE and E. The Middle Allochthon as the tectono-stratigraphically lowest unit of the area solely consists of meta-arkose. The Upper Allochthon exposed in the area as Köli-subnappe is composed of quarz-phyllite and meta-gabbro. In summary, all units of the working area experienced regional-metamorphic overprint, with the metamorphic grade decreasing from the Upper to the Middle Allochthon.

The aim of this investigation was to determine more accuratly the position and the end of the nappe-intern duplex of the Middle Allochthon and will provide a more precise insight into the deformation history of the Fjällfjäll Window. Through lithological investigation and the collection of tectonical data the internal overthrusting could be captured more precisely. The microscopic analysis of the samples allowed the reconstruction of the p-T-conditions during the Caledonian Orogeny in the northern Fjällfjäll Window. Furthermore, 3D-modeling of the nappe-duplex in the working area will allow a spatial understanding of the nappe-structures.

**References**

D. Budach & T.J. Degen, (2013): Struktur und Metamorphose im Norden des Fjällfjäll-Fensters in den Skandinavischen Kaledoniden (Västerbotten, Schweden), Hallesches Jahrbuch für Geowissenschaften, Band 35, S. 27-74

T.J. Degen (1997): Deformation and metamorphism in the area between Borgafjäll and Børgejfell in the northern Caledonides of Scandinavia (Jämtland/Västerbotten), Hallesches Jahrbuch für Geowissenschaften, Reihe B, Beiheft 2, S.1-100

**Talk**

## 14C AMS dating of enriched pollen samples – Flow Cytometry as an optimized purification application

**Christoph K. Steinhoff**, **Nadine Pickarski, Thomas Litt**

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Radiocarbon dating of terrestrial plant-remains is a traditional method for age estimations of lake sediments. The absence of sufficient large plant macrofossils required for AMS dating in continental records, especially larger lakes, outlines the limitation of this dating application. Due to their ubiquitous presence in sedimentary archives, especially pollen samples are suitable for radiocarbon dating. Nevertheless, their isolation and purification without significant carbon contamination still presents a challenge. Flow cytometry offers a possibility to separate huge quantities of pollen in a short period of time and additionally allows the removal of detrital particles at the same time. The combination with a gas ion source for AMS measurements enables not just the isolation of pollen from heterogeneous sediment samples and the age estimation of purified pollen samples, but a significant reduction of the required sample weight to less than 100 µg carbon content as well.

In this study we present an evaluation and optimization of the processing steps of the chemical pretreatment and flow cytometry. Different sediment samples gathered from the Lake Holzmaar (Western Eifel) and Lake Van (Eastern Anatolia) were used to evaluate the influence of the sediment composition on the purification process. We observed a strong relation between the sample's organic matter, the result of the pollen isolation, and the AMS dating, ameliorating with decreasing detrital content. In addition, larger proportions of foreign particles were observed with increasing pollen size in the purified sample. Although it is possible to identify different plant genus by scattered light and fluorescent properties, an isolation of separate pollen populations without contamination by undefined plant-particles remains difficult.

Our results demonstrate the importance to remove large detrital particles from the sediment sample before the cytometric analysis, and that a refinement for pollen population separation is needed. Therefore, it is necessary to adjust the processing steps to the pollen concentration and the pollen spectra expected for each sample. This allows a precise distinction between pollen and non-pollen and prevents an increased percentage of foreign particles in the purified sample. A standardization of the presented laboratory routine for the purification of pollen samples using flow cytometry will allow analysis and separation of vast amounts of samples in a short period of time. In consequence, dating of enriched pollen samples can be used as a robust contribution and independent time control of existing age estimations of lake sediments in continental records, e.g varve chronologies.

**Poster**

## Microplastic accumulation in different sedimentary environments of patch reef systems (Kepulauan Seribu complex, Indonesia).

**Dwi Amanda Utami**[1,2], **Lars Reuning**[1]

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Presently the most abundant marine litter is plastic. Marine litter is accumulated at the beach, floating on the oceans, and a large proportion is projected to sink and remain on the seafloor. Microplastic accumulates in benthic sediments and shorelines with harmful effects to the environment due to its small size. Ingestion of microplastic by reef corals with potentially detrimental effects on coral growth was observed in laboratory experiments. Microplastic is reported to have the ability to adsorb toxic chemicals from surrounding sea water which can be pathologic if consumed by marine animal. Plastic waste also carries pathogens that are held responsible for the outbreaks of disease on coral reefs. Microplastic therefore poses a threat to reef corals and their ability to act as framework builders in coral reef systems. Despite this, microplastic accumulation in reef systems remains largely unquantified. We aim to analyze the control of sedimentary processes on the distribution of microplastic in different sedimentary environments. Microplastic is investigated in the surface marine sediments of the subtidal lagoon, the reef margin, the sand apron with variable sea grass cover and the intertidal beach. Potential sources for microplastic are mismanaged waste from densely populated islands, marine fishing, aquaculture and tourism. The result will contribute to a better understanding of the sedimentary processes that govern microplastic accumulation and distribution within different environmental setting.

Poster

## YOUNG ISDR, a new international platform for early career diatomists

**Hannah Vossel**[1], **Andrea M. Burfeid Castellanos**[2], **Benito Xavier**[3]

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During the International Diatom Symposium held in Quebec City (Canada) in 2016, the "Young ISDR" section within the International Society of Diatom Research (ISDR) was launched. The idea behind this formation is (a) to address the interests of early career diatomists directly to the ISDR commitee by an elected early career representative and (b) to assist early career researchers to build collaborations and develop skills needed for career enhancement. A better exchange with experienced diatomists should be facilitated providing workshops dealing with key topics of diatom research within future congresses, such as during the next International Diatom Symposium held in Berlin in June 2018. The Young ISDR also tries to improve global networking with other international scientific organisations and related diatom research topics.

Here, we would like to present a newly created socializing network of Young ISDR members including an interactive forum and a blog (https://youngisdr.blogspot.de/), which both highlight job offers, possible funding, future workshops and conferences, research reports and key publications within the field of diatom research.

Poster

## Base flow colloidal and truly dissolved distribution of particle-reactive rare earths and yttrium in the Kalix and Råne Rivers, Northern Sweden, reveal a terrestrial origin of seawater REY patterns

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Rivers are the major source of trace elements like rare earth elements and Y (REY), to the oceans. The net flux into the ocean is determined by the association of these elements with the individual "physical" element "pools" in river water, i.e., suspended particles (<0.2 µm), nanoparticles and colloids (NPCs; >1kDa) and the truly dissolved fraction (<1KDa). In this study, we investigated the distribution of REY in the particle size fractions <1 KDa, 1 KDa - 10 KDa, 10 KDa - 0.2 µm, and >0.2 µm in the boreal Kalix and the Råne rivers during three consecutive days of low river discharge. The two pristine rivers are not regulated and flow into the Baltic Sea. The Kalix River source in the Caledonia mountains (400-1000 Ma) comprises mica schists, quartzites and amphibolites and has a catchment area of 18,130 $km^2$. The Råne River represent the outflow of Lake Råne Träsk (located on 1.8 Ga granitic basement) and has a smaller catchment area around 4207 $km^2$.

Boreal rivers often show a flat REY pattern, but may show strong seasonal changes [1]. Our REY results for the Kalix and the Råne rivers show these flat patterns in the total dissolved fraction (<0.2 µm), with a negative Ce anomaly. The NPCs and the truly dissolved fraction show a strong difference between the heavy and light REY. This is reflected by increasing HREY/LREY and Y/Ho ratios with decreasing filtration pore size. In the dissolved fraction (<0.2 µm) of the Kalix River, 16-20 % of LREY and 38-54% of HREY are bound to small organic NPCs between 1 KDa and 10 KDa, and only 2 -3% of LREY and 6-12% of HREY are truly dissolved. In the Råne river about 3-4% of LREY and 6-9% of HREY are truly dissolved. The truly dissolved fraction in both rivers have very similar REY distribution patterns that resemble those of seawater. This corroborates recent studies suggesting that the REY patterns of the truly dissolved pool of river water reflects the REY distribution in seawater [2,3], implying that the major REY fractionation between the REY in seawater and their upper continental crustal source occurs during *terrestrial* weathering and REY mobilisation, and not within the marine environment.

[1] Pokrovsky et al. (2014) Ocean Sci. 10, 107-125.

[2] Merschel et al. (2017) Geochim. Cosmochim. Acta 213, 383-399.

[3] Pourret, O. and Tuduri, J. (2017) Scientific Reports 7, Article number: 5857.

Poster

## Geochemistry and Petrology of volcanic rocks from the BARB1 and BARB2 drill cores of the Komati Formation, Barberton Greenstone Belt, South Africa

**Stefanie Weinstock**[1], **Chris S. Marien**[2], **Chris Ballhaus**[1], **Allan Wilson**[3], **Carsten Münker**[2]

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The ICDP Baberton Project drilled in 2011 yielded new insights into the volcanic processes, crustal evolution and mantle processes during Paleoarchean time. As type locality for komatiites, a rock type almost exclusively bound to the Archean, the Barberton Greenstone belt had previously been closely investigated (e.g. [1], [2]). The Barberton drilling project provided a continuous stratigraphic sequence, and a wealth of relatively unaltered samples became available. However, only a total of 225 samples out of the 850 drilled meters have been studied in detail so far.

In order to elucidate the petrogenesis of volcanic rocks from the Komati Formation and to compare the drillcore rocks to already existing data (e.g. [3], [4]), we performed major and trace element measurements on 21 selected logs, taken at various depths from the cores

BARB 1 and BARB 2. The logs were selected for their degree of preservation, following previous reconnaissance geochemical and petrographical work, respectively. Even though special care was taken, many primary igneous minerals are highly altered, and fresh pyroxene and olivine are only preserved in a few samples. However, all samples display well preserved magmatic structures, that allow inferences on the petrogenesis of the samples. Based on major element data, the 21 selected bulk samples can be classified as Al-depleted komatiites, which is in good agreement with previous works (e.g. [2], [4]). We are currently carrying out detailed petrographical investigations as well as further trace element and isotope analyses (Lu-Hf, Sm-Nd).

[1] Arndt et al. (2008). Cambridge university press.

[2] Robin-Popieul et al. (2012). Journal of Petrology, 53(11), 2191-2229.

[3] Coetzee (2014). Doctoral dissertation.

[4] Blichert-Toft et al. (2015). American Mineralogist, 100(11-12), 2396-2411.

**Poster**

## Geomagnetic investigation of a crashed military JU88 Aircraft in Lake Zwischenahn

**Robin Zindler, Kilian Pallapies, Fynn Warnke**

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During our self-organized geophysical student project an array of three GSM 19 Overhauser Gradiometers by GEM Systems was used to localize a german JU88 military aircraft in lake Zwischenahn in Lower Saxony, Germany. In 1942, two aircraft collided over the military airport of Rostrup, crashed into the lake and sank down through the muddy sediments. While one of the aircrafts was recovered, the second one including the crew still remains in the sediments. Due to the meter-thick muddy conditions and shallow water depths throughout the whole lake a near-surface geophysical survey method with terrestrial magnetometers above the water surface was used. Aim of the project was to develop and apply a towed magnetometer configuration optimized for these specific lacustrine conditions.

Therefore, a non-magnetic catamaran was constructed by connecting two kayaks with a wooden cross-beam carrying three Overhauser gradiometers with two individual sensors each. They were mounted with a spacing of 1.5 m apart, resulting in a total across track coverage of approximately 7.5 m. This floating magnetometer platform was towed by a motorized Zodiac in 20 m distance. Handheld navigation was used for the Zodiac while the sensor positions were determined by two GPS antenna on the kajaks.

Based on eyewitness reports and oral transmissions we narrowed the aircrafts position down to the south-western part of lake Zwischenahn. Two grids with areas of 150 m x 200 m and 200 m x 250 m with a total of 69 measured profiles were surveyed. After different correction steps our data revealed the location of a large dipole-anomaly in the lake where we are expecting the plane wreck.

**Talk**

## Element distribution including rare earth elements and yttrium in fruit bodies of the bolete mushroom Suillus luteus

**Anna-Lena Zocher, Dennis Krämer, Gila Merschel, Michael Bau**

*Jacobs University Bremen, Germany*

Many fungus species are edible and consumed by humans. While major, toxic and radioactive elements have been studied extensively, little is known about uptake and distribution of rare earth elements and yttrium (REY) in fungi as reliable data are seldom available. The continuously growing use of REY in high technologies is coupled with an increasing release of anthropogenic REY into the environment, which may thus impact living organisms.

Here, we report major and trace element data, including REY, for fruit bodies and their different compartments (cuticle, flesh of cap, tubes & pores, stipe) of the bolete fungus *Suillus luteus*. Concentrations of all elements vary within the fruitbodies. Most elements are mainly stored in the cap, REY are most abundant in the cuticles. Only P, K, Zn, Rb, and Cs are enriched in the compartments compared to ambient soil. The total REY concentrations are rather low with 13.1 mg $kg^{-1}$ in dry matter (DM) to 72.6 mg $kg^{-1}$ DM and 13.4 mg $kg^{-1}$ DM to 74.2 mg $kg^{-1}$ DM in the different compartments and whole fruit bodies, respectively. A common feature of the four compartments is the similar flat shale-normalized REY pattern resembling the patterns of surrounding soil. However, only the compartments have positive Y anomalies and, in many samples, also positive La anomalies. Light REY (LREY) are slightly depleted relative to heavy REY (HREY) in cuticles and whole fruit bodies, whereas the other three compartments are rather slightly enriched in LREY relative to HREY. Middle REY (MREY) are more fractionated from HREY than LREY from MREY. Like many ectomycorrhizal fungi, *Suillus luteus* releases iron-chelating compounds. But soil leaching experiments with the hydroxamate siderophore desferrioxamine B indicate that these siderophores barely influence the uptake of REY to fruit bodies. Due to the negligible fractionation in combination with the resemblance of the REY distribution in fruit bodies and ambient soil, fungi may potentially serve as bioarchives for tracers in geochemical exploration.

Imprint

Book of Abstracts
GeoBonn 2018
Living Earth, 2-6 September 2018 | Bonn

Rheinische Friedrich-Wilhelms-Universität Bonn, Steinmann-Institut für Geologie, Mineralogie und Paläontologie
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