# HALLESCHES JAHRBUCH FÜR GEOWISSENSCHAFTEN

BEIHEFT 51

## 19TH SYMPOSIUM TECTONICS, STRUCTURAL GEOLOGY AND GEOLOGY OF CRYSTALLINE ROCKS

R. KÜHN, S. SCHNAPPERELLE, R. KILIAN, D. MERTMANN, M. STIPP (EDS.)

## VOLUME I: ABSTRACTS

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Volume I: Abstracts

# 3D structural modelling of Variscan metasedimentary rocks in the western Harz Mountains, Germany: implications for geothermal exploration

Ali Abdelkhalek, Bernd Leiss, David Charles Peter Peacock, Bianca Wagner
Georg-August-Universität Göttingen, Germany

The Harz Mountains show exposures of the NE–SW striking Rhenohercynian fold-and-thrust belt. This study focuses on the western part of the Harz Mountains, ∼ 40 km NE of Göttingen, central Germany. The lithologies and structural styles of the Variscan metasedimentary rocks (Devonian and Lower Carboniferous) in the western Harz Mountains are expected to occur in the sub-surface of Göttingen in a depth of ∼ 1.5 km. These rocks are being examined for their potential as an Enhanced Geothermal System (EGS) reservoir, with the western Harz Mountains being used as an analogue location. The main objective of this work is to construct a 3D geological model of the western Harz Mountains representing the deformation styles at ascale that would be compatible with the overall structure of a deep geothermal reservoir. We had to focus on using relevant data to create a conceptual lithological and structural model that can be used for geothermal exploration and exploitation. The following data were compiled and implemented: i) information about lithologies and ages of rocks, bed dips, folds and faults measured in the field; ii) lithologies and ages of rocks, bed dips and faults from eight boreholes in the western Harz Mountains; iii) published geological maps and digital elevation model of the area. Two NW-SE geological cross-sections were constructed in the northern part of the study area, as a basis to construct a km-scale 3D model of the structures. The Variscan metasedimentary rocks in the western Harz Mountains are deformed by heterogeneous NW-verging folds and reverse faults. The folds were cut by ∼ $NW - SE$ striking extensional and strike-slip faults, which are probably post-Variscan. These faults influence post-Variscan mineralisation in the region, which implies that these faults are significant for fluid flow in the reservoir, whether they are sealed or open.

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# The SpannEnD project – Prediction of the recent crustal stress field of Germany

Steffen Ahlers[a], Sophia Morawietz, Luisa Röckel, Karsten Reiter, Tobias Hergert, Andreas Henk, Birgit Müller, Oliver Heidbach

[a]TU Darmstadt, Germany

The crustal stress field is important for many scientific questions and underground applications e.g., slip-tendency analysis of faults, borehole stability or the search of a high-level nuclear waste deposit. However, the knowledge for Germany is quite low. It is mainly based on the World Stress Map (WSM) which provides the orientation of the maximum horizontal stress ($S_{Hmax}$) and the stress regime. Information about the absolute stress field i.e., stress magnitudes are rare. Therefore, the SpannEnD (Spannungsmodell Endlagerung Deutschland) project aims to improve this knowledge by data compilation and a geomechanical-numerical model. As a first step a magnitude compilation for Germany including a quality ranking system has been published as an open-access database. To achieve a continuous prediction from these pointwise data a geomechanical-numerical 3D model calibrated with magnitudes of the minimum horizontal stress ($S_{hmin}$) and $S_{Hmax}$ is used. The model contains 22 units parametrized with individual mechanical properties. Linear elasticity is assumed and the finite element method (FEM) is used to solve the equilibrium of forces. Overall, the model contains about 11 million hexahedral elements resulting in a lateral resolution of 2.5 x 2.5 km$^2$ and a vertical resolution of up to 250 m. The models results are in a good agreement with $S_{hmin}$ and $S_{Hmax}$ magnitudes – calibration data and additional data records - and the orientation of $S_{Hmax}$ from the WSM. Accordingly, our model enables for the first time a prediction of the complete stress tensor of the upper crust of Germany.

# Deep structure of the East European Craton at the transition from Sarmatia to Fennoscandia as interpreted from the TTZ-South seismic profile (SE Poland to Ukraine)

Paweł Aleksandrowski[a], Andrzej Głuszyński[a], Tomasz Janik, Vitaly Starostenko, Tamara Yegorova, Wojciech Czuba, Piotr Środa, Anna Murovskaya, Khrystyna Zajats, James Mechie, Katerina Kolomiyets, Dmytro Lysynchuk, Dariusz Wójcik, Victor Omelchenko, Olga Legostaieva, Anatoly Tolkunov, Tatiana Amashukeli, Dmytro Gryn, Serhii Chulkov

[a]Polish Geological Institute, Wrocław, Poland

The TTZ-South regional seismic profile runs NW-SE, roughly along the Teisseyre-Tornquist zone (TTZ) at the SW margin of the East-European craton (EEC), near its junction with the Paleozoic platform of northwestern Europe. The results obtained from this profile reveal a complex geometry of the upper crust, interpreted here as representing the NW-vergent and NE-SW striking overthrust-type, Paleoproterozoic ($\sim 1.84 - 1.8$ Ga) Fennoscandia-Sarmatia suture (FSS) at the contact between the two major segments of the EEC. The overthrust continues down-dip into the middle and lower crust, showing a crustal-scale staircase trajectory. A composite internal structure of the southeastern, Sarmatian, craton segment is interpreted as comprising two tectonically juxtaposed major crystalline basement units of dissimilar crustal structure, overthrust to the NW, namely the southern, Moldavo-Podolian, devoid of a lower crustal layer, and the northern, Lublino-Volhynian, units. On the leading, NW, edge of the latter unit, two smaller-scale thrust slices, representing marginal Sarmatian terranes are distinguished. The results of the TTZ-South project, combined with those of other nearby deep seismic profiles, are consistent with continuation of the East European crystalline cratonic basement across the TTZ from the NE to SW and its plunging into the deep basement of the Paleozoic platform. Effects of a late-stage, extensional deformation responsible for the origin of the mid to late Proterozoic ($\sim 1.4-0.6$ Ga), SW-NE trending Orsha-Volhynia rift basin (aulacogen) are also probably recorded in the uppermost crustal layer. A thick Ediacaran succession, deposited in this basin, must have been later tectonically thickened due to Variscan orogenic deformation. The Moho depth varies between 37 and 49 km, resulting in the thinnest crust in the SE, quick changes across the TTZ, and slow shallowing from 49 to 43 km in the NW. The abrupt Moho depth increase to the NW from 43 to 49 km at around the middle of the transect, is considered to reflect the overlying Sarmatian lower crust as being overthrust upon that of Fennoscandia and, thus, resulting in the lower crust tectonic duplication. Subhorizontal and wavy seismic boundaries below the Moho, at depths from 53 to 80 km, can be indicative of large-scale thrusting and folding in the uppermost mantle.

# Inside the fault core in the footwall of Simplon Fault Zone (Central Alps): did ductile mechanisms allow this low-angle fault to slip?

Valentina Argante[a], David C. Tanner[a], Christoph Von Hagke[b], Christian Brandes[c], Sumiko Tsukamoto[a]

[a]Leibniz Institute for Applied Geophysics, Hanover, Germany, [b]University of Salzburg, Department of Geography and Geology, Salzburg, Austria, [c]Leipniz Universität, Hanover, Germany

Clasts as well the matrix within a gouge zone may conserve different phases of the deformation history of a fault. We carry out microstructural analysis on a gouge from the footwall of one of the major normal faults of the Alps, the Simplon Fault Zone. The latter is a low-angle normal fault consisting of a several meter thick mylonitic zone overprinted by a few dm narrow cataclastic zone with the same kinematics. Although many studies have been carried out on this fault, its evolution from ductile to brittle deformation is still under discussion. Our work shows the kind of deformation mechanisms, from brittle to ductile that took place within the fault core of the Simplon Fault Zone. We attempt to answer to the question whether ductile mechanisms did allow this low-angle fault to slip. Commonly, low angle normal faults are not well oriented with the extensional stress field to slip. One of the possible factors that can favour slip on such a normal fault could be the presence of clay minerals. Our results from micro-structural analysis show grain boundary migration features on folded quartz veins. This suggests that the protolith of the fault zone was at high temperature conditions, $T>600$ °C, during previous dynamic deformation. The presence of chlorite and muscovite indicates that the rock was exposed to low temperature and pressure conditions (greenschist facies, $T=300$-$400$ °C, $P=0.2$ GPa), but they can also explain the reason for low angle normal faulting. Pressure-solution mechanisms affect both quartz and greenschist paragenesis, indicating their formation at shallow depths. The last deformation was purely brittle, as shown by vertical calcite veins and fractures in quartz. It suggests a near-surface position of the fault, characterized by extensional and opening mechanisms. This multitude of deformation phases within the gouge zone indicate a continuous exhumation history from high to low temperatures, with clear cross-cutting relationships, even if we do not observe cataclasite features. To explain this, we propose two possibly coexisting scenarios: the first in which the footwall maintained a high temperature over a long time, which inhibited cataclastic processes, and a second, where the clay minerals accommodate deformation by creeping, allowing the fault to slip.

# The inversion of a passive continental margin portrayed by a 2D balanced kinematic forward model across the Velebit Mountains in the northern external Dinarides fold and thrust belt.

Philipp Balling[a], Bruno Tomljenović[b], Kamil Ustaszewski[a]

[a]Friedrich-Schiller-Universität Jena, Germany, [b]Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Croatia

The Late Cretaceous collision of the Adriatic Microplate with Eurasia resulted in an overall SW vergent and in-sequence structural architecture of the Dinarides fold and thrust belt. Subsequent outward propagation of the deformation front led to high crustal shortening within the external Dinarides between Mid-Eocene and Late Oligocene times. The external Dinarides are built up by mainly Mesozoic carbonate platform rocks, deposited in an extensional passive margin setting. Fault kinematic data and balanced cross-sections across the external Dinarides suggest an along-strike contrasting style of Cenozoic deformation, separated by the Split-Karlovac Fault, a c. 250 km long dextral transpressive tear fault. This fault delimits a southern, SW-vergent nappe stack segment affecting southern Dalmatia around Split from a northern, NE-vergent backthrust dominated segment affecting northern Dalmatia around Zadar. So far, it was not known why the regionally rather uniform Mesozoic Adriatic carbonate platform sequence had undergone such contrasting along-strike deformation.

To better understand the cause for the initiation of the NE-vergent backthrusts and to determine the amount of Cenozoic crustal shortening within the northern segment of the external Dinarides, we applied a 2D kinematic forward model approach across the southern Velebit Mountains. The Velebit Mountains extend for over 145 km along the northern Adriatic coast and form a fault-related SW-dipping monocline. This monocline is cored by a NE-vergent backthrust .With the applied method we simulated various scenarios and different geometries for the Mesozoic extension and the Cenozoic contraction in a trial-and-error fashion for individual faults to resemble the present-day deformed section from an initial horizontal layer cake model.

Our best-fit and balanced kinematic model across the Velebit Mountains portrays a 68 km wide triangle structure underneath the Velebit Mountains. This triangle structure took up at least 47 km of shortening and consist of a set of thin-skinned NE-vergent back (roof) thrusts detaching in Mesozoic strata atop a SW-vergent thick-skinned antiformal stack involving Paleozoic successions. Pronounced across-strike facies and thickness changes in the Triassic and Jurassic successions suggest that normal faults related to the formation of the Adriatic passive margin played a role in predetermining the position of later contractional structures. The best-fit 2D kinematic forward model shows that the inversion of thick-skinned half graben initiated the NE-vergent back thrust. This demonstrates that the inversion of normal faults played a crucial role in the Cenozoic deformation of the Dinarides fold and thrust belt and ultimately led to the contrasting along strike deformation in its external part.

# Quaternary faulting in the Eastern Alps: paleostress regimes and time constraints of caves passage offsets

Ivo Baroň[a], Jacek Szczygieł[b], Rostislav Melichar, Lukas Plan, Bernhard Grasemann[c], Eva Kaminsky, Denis Scholz,

[a]Department of Geology and Paleontology, Naturhistorisches Museum, Vienna, Austria, [b]University of Silesia, Poland, [c]University of Vienna, Austria

Since the Miocene, the Eastern Alps have been undergoing eastward lateral extrusion compensated by strike-slip faulting and N-directed thrusting leading to several paleostress phases. So far, geologists have focused primarily on the main lateral extrusion phase. The geologic record of younger phases is poorly constrained, and the knowledge gap on Quaternary tectonics of the Eastern Alps is only filled by scattered research on individual faults. Since karst cave passages may serve as the geomorphic displacement indicators and provide timing constraints via U-Th dating of broken speleothems, we analyzed 201 Quaternary fault ruptures in a total of 30 caves in the Eastern Alps, some of them radiometrically dated. Reactivated faults have been recorded with their orientation, slip vector, and offset in caves adjacent to major fault systems of the Eastern Alps. Using the multiple inversion method for heterogeneous fault-slip data, we computed the paleostress.

In the Northern Calcareous Alps, where caves are most abundant, tens of active, mostly oblique normal strike-slip faults were documented in massifs adjacent to sinistral Königsee-Lammertal-Traunsee Fault in Hoher Göll, Tennengebirge, and Hagengebirge massifs. The dominating associated paleostress regimes are the extensional ones with NW-SE, and NNE-SSW oriented $\sigma 3$ and the transtensive regime with $\sigma 1$ slightly plunging to N and $\sigma 3$ to SE. The transtension with N-S $\sigma 1$ have been also recorded in the Dachstein massif bounded by Salzach-Ennstal-Mariazell-Puchberg fault. Further to the east, In the Totes Gebirge and Hochschwab massifs, $\sigma 1$ change orientation to SE-NW with $\sigma 3$ varied plunge in NW-SE trend, and regime locally changing form transpressive to transtensive. From the NNE-SSE, ESE-WNW, and ENE-WSW striking active faults along the sinistral Mur-Mürz Fault zone, the strike-slip regime with SW-NE $\sigma 1$ was computed. Most active faults in caves along the southern part of the sinistral Vienna Basin Transfer Fault were NW-SE and NNE-SSW oriented with normal to sinistral kinematics and cumulative offsets of a few mm to a couple of cms. Here dominating extensional regime with vertical $\sigma 1$ and $\sigma 3$ varied from E-W, NW-SE to N-S, which generally agreed with the Vienna Basin's opening mode along this sinistral fault system. In the local shear zone of the Lavanttal fault near Judenburg, only a few oblique reverse or oblique normal faults with active offset were documented, which revealed a transtensive regime with E-W $\sigma 3$ and subhorizontally $\sigma 1$. Along the tectonic contact between the Eastern and the Southern Alps, the dextral Periadriatic Line polyphase sinistral and reverse-dextral NE-SW striking secondary faults were documented at the sinistral Obir Fault. Late Pleistocene to Early Holocene reactivations and up to 40 cm offsets have been documented there. The paleostress states of this large-scale shear complex of Karawanken Mts. are expressed by a transpressive regime with NNW-SSE $\sigma 1$ and transtensive regime with NE dipping $\sigma 1$ and NW-SE oriented $\sigma 3$. In conclusion, fault-slip data preserved in Quaternary cave passage ruptures brought original information on the paleostress regime over a significant portion of the Eastern Alps in their latest deformational period.

# Petrological-geochemical comparison of two zoned Carboniferous plutons of the Pyrenees (Bassiès, Marimanha)

Till Berndt, Stephan Schnapperelle, Michael Stipp
Martin-Luther-Universität Halle-Wittenberg, Germany

In the course of the current debate about the Variscan orogeny in the Pyrenees, the mechanisms and timing of emplacement for numerous Variscan granitoid plutons in the Axial Zone of the Pyrenees are revisited. They are hardly affected by Alpine deformation and thus allow a plain view on the Variscan emplacement conditions. The objective of this work is to carry out structural, petrological and geochemical investigations of the Bassiès pluton and the Marimanha pluton, using modern methods of digital image analysis. Based on the results, emplacement and deformation of the two plutons within the related tectonic setting will be compared.

In geological map view, both plutons show an internal lithologic zonation from felsic leucogranites in the core to granodiorites at the periphery. In the field, deformation fabrics can only be observed at the periphery, mostly in the form of a magmatic foliation marked by aligned biotite grains. The emplacement of the Bassiès pluton occurs synkinematically along a strike-slip fault that is active before D2, possibly during D1, according to AMS studies and structural investigations of the contact aureole. The Marimanha pluton shows magnetic foliations and lineations with dominant NE-SW strike. Various authors favor emplacement within a dextral-transpressive regime with NNW-SSE shortening, hence synkinematically with D2-b.

The mineral assemblage of the samples quantified by digital image analysis and additional geochemical measurements confirm an internal lithologic zonation of the plutons and a classification as peraluminous S-type granites. However, since this zonation does not represent a linear magmatic differentiation trend from the core to the rim, a relatively complex mode of emplacement is indicated.

For the structural investigations also digital image analysis was used to quantify the fabrics in thin section scale. The samples of the Marimanha pluton showed only weak shape preferred orientations of the individual mineral phases within foliation planes. These are more pronounced towards the rim than in the center of the pluton. The formation of such a weak magmatic foliation as a result of a regional transpressive regime is conceivable (D2?). The samples of the Bassiès pluton exhibits somewhat stronger preferred orientations, also increasing towards the rim, which can qualitatively be interpreted as an indication of larger strain during emplacement in comparison to the Marimanha pluton. This could be either due to a more intense deformation, or a longer lasting syntectonic emplacement, possibly due to an earlier intrusion (during D1?), or both. The deformation increasing towards the rim as well as the generally sparse solid-state deformation fabrics in the thin sections of both plutons indicate that the given foliations and preferred orientations are of (late) magmatic origin.

## Influence of deformation and fluids on Ti exchange in natural quartz

Michel Bestmann[a], Giorgio Pennacchioni[b], Bernhard Grasemann[c], Benjamin Huet[d], Michael W.M. Jones[e], Cameron M. Kewish[f]

[a]FAU Erlangen-Nürnberg, Germany, [b]University of Padova, Italy, [c]University of Vienna, Austria, [d]Geological Survey of Austria, Vienna, Austria,[e]Queensland University of Technology, Brisbane, Australia, [f]Australian Synchrotron, ANSTO, Clayton, Australia

For over 10 years, the TitaniQ geothermometer has been used to constrain deformation temperatures in quartz-rich rocks. The calibration of the thermometer rests on the direct correlation of the titanium trace element concentration in quartz with respect to the ambient temperature. However, the processes and parameters which lead to re-equilibration of the Ti-in-quartz system during deformation are not yet fully understood. Here we analysed deformed quartz veins from the Eastern Alps (Prijakt Nappe) applying a combination of microstructural, spectroscopic, and geochemical analyses. In contrast to recent studies which highlight the importance of stain, we show that the availability of free grain boundaries, fluids, and their partitioning play the dominant role in Ti resetting towards lower concentrations in our studied case of retrograde deformation. We employ a robust analytical approach to investigate the interplay between grain-scale deformation, fluid-rock interactions, and geochemical exchange during increasing strain in the quartz mylonites. With this approach, the microstructures representing most re-equilibrated sites for the application of the titanium-in-quartz geothermometer can be readily identified, even at lower greenschist facies deformation conditions and a recrystallization regime dominated by subgrain rotation.

These coarse-grained quartz veins, that formed at amphibolite facies conditions, were overprinted by lower greenschist facies deformation to different degrees. During the overprint, subgrain rotation recrystallization was dominant during progressive deformation to ultramylonitic stages. The initial [Ti] (3.0-4.7 ppm) and cathodoluminescence (CL) signature of the vein crystals decrease during deformation mainly depending on the availability of fluids across the microstructure. The amount of strain played a subordinate role in resetting to lower [Ti] and corresponding darker CL shades. Using a microstructurally-controlled analysis we find that the most complete re-equilibration in recrystallized aggregates ([Ti] of 0.2-0.6 pm) occurred (i) in strain shadows around quartz porphyroclasts, acting as fluid sinks, and (ii) in localized microshear zones that channelized fluid percolation. [Ti] resetting is mainly observed along wetted high angle boundaries (misorientation angle $> 10 - 15^{\circ}$), with partial [Ti] resetting observed along dry low angle boundaries ($< 10 - 15^{\circ}$). This study shows for the first time that pure subgrain rotation recrystallization in combination with dissolution-precipitation under retrograde condition provide microstructural domains suitable for the application of titanium-in-quartz geothermobarometry at deformation temperatures down to 300-350 °C.

# Exploring the physical state of Germany's lithosphere by means of data-integrative 3D geological models

Judith Bott[a], Magdalena Scheck-Wenderoth[a], Mauro Cacace, Denis Anikiev
[a]GFZ German Research Centre for Geosciences, Potsdam, Germany

Subsurface temperatures are of key interest for a systematic and sustainable exploitation and storage of georesources (such as geothermal energy). At the same time, temperature is a key factor to control rock deformation mechanisms and thus the tectonic response of a region to geodynamics. Over the past decade, we have explored diverse regions of Germany for their regional geothermal potentials by means of lithospheric-scale 3D geological models that were utilized for (coupled) thermal and hydraulic process simulations. This augmented our understanding of heat transport processes in different tectonic settings as the Upper Rhine Graben and the Northeast German Basin and enabled us to derive physics-based temperature predictions for parts of the systems where direct observations (borehole measurements) are missing. More recently, we have used such thermal models also to assess the long-term mechanical behaviour of the crust by means of 3D rheological models which gave us new insights into potential causes for the distributed seismicity in SW Germany.

The predictive capability of such numerical models strongly depends on a realistic description of the subsurface configuration of rock physical properties, in other words on an appropriate 3D structural geological model. Hence, our research is based on developing both software for coupled thermal-hydraulic-mechanical process simulations and efficient workflows for the integration of diverse geological and geophysical data including borehole, seismic, seismological and gravity field data. In this talk, I will give an overview of the open-source software developed in our group while presenting examples of regional 3D geological models that broadened our understanding of the thermal field of Germany from the lithospheric mantle up to the Earth's surface. Based on this, I would like to discuss what would be further required to improve our digital twin of the lithosphere of Germany ("3-D-D") so as to properly use it for decision making in the fields of georesources and waste disposal management.

# Fast stress-loading and -unloading during faulting and shock indicated by recrystallized grains along quartz cleavage cracks

Lisa M. Brückner[a], Fabian Dellefant, Claudia A. Trepmann[a]
[a]Ludwig-Maximilians-Universität München, Germany

Recrystallized quartz grains are localized along cleavage cracks in coarse original quartz grains within pseudotachylyte-bearing gneisses from the Silvretta basal thrust, Austria, and in shock-vein-bearing gneisses from the Vredefort meteorite impact structure, South Africa.

In the fault rocks of the Silvretta nappe, the recrystallized grains along two sets of $\{10\bar{1}1\}$ cleavage cracks at an angle of about 90° occur in rounded quartz clasts with a diameter of several tens of mm to cm embedded within pseudotachylytes. No evidences of shear offset were found in relation to the cleavage cracks. The fine-grained recrystallized grains have diameters of about $10 \pm 6$ $\mu$m or less and are slightly elongated parallel to the cleavage planes. These new grains have similar but also deviating crystallographic orientations to that of the host. As these quartz microstructures occur exclusively in spatial relation to pseudotachylytes, they are interpreted to result from the associated high stress/high strain-rate deformation. Mechanical $(\bar{1}01)$ twins in amphibole revealed stresses on the order of 400 MPa during formation of the pseudotachylytes. Yet, the new quartz grains do not show evidence of deformation after their growth, i.e., no internal misorientation, no crystallographic preferred orientation related to dislocation glide. Therefore, we suggest that the secondary quartz grains formed during annealing after the pseudotachylyte-forming event localized at the damage zone surrounding the cleavage cracks at quasi-isostatic stress conditions. Very similar microstructures are found in Archean gneisses of the Vredefort impact structure, South Africa. There, the recrystallized grains with diameters of few $\mu$m along $\{10\bar{1}1\}$ and (0001) cleavage planes occur in shocked quartz grains related to mm-sized shock veins, characterized by Schlieren-microstructure of secondary feldspar. Also here, no major shear offset of the cleavage cracks is obvious and the secondary quartz grains do not show evidence of deformation. The observation that quartz shock effects are spatially related to both, the shock veins and secondary quartz grains, suggests that they formed during shock loading and subsequent pressure release with high strain rates but minor shearing. Analogous to the Silvretta fault rocks, growth of quartz grains is suggested to occur restricted to the damage zone of the cleavage cracks at quasi-isostatic stresses during post-shock annealing.

In both, the Silvretta fault rocks and shocked gneisses from the Vredefort dome, quartz grains fractured without major shearing at high stresses and subsequently recrystallized localized to the damage zone of cleavage cracks at quasi-isostatic stress conditions. Damage in the process zone surrounding the cleavage cracks must have been large enough for effective grain boundary migration, i.e., growth of grains in orientations weakly controlled by the host orientation. Recrystallization ceased because of the missing driving force during subsequent quasi-isostatic stress conditions. These microstructures indicate quasi-instantaneous loading to high differential stresses of a few hundred MPa and fast unloading to quasi-isostatic stress conditions.

# Seismically induced Bookshelf-Mechanism in soft marine muds of the Muschelkalk carbonates in the Germanic Basin: A possible genesis for Querplattung

Bryce Carr[a], Nikolaus Froitzheim[b], Ruth Keppler[b], Rüdiger Kilian[a]
[a]Martin-Luther-Universität Halle-Wittenberg, Germany, [b]University of Bonn, Germany

The Querplattung (also Sigmoidalklüftung) are generally regarded as synsedimentary, en-echelon joints or vein structures constricted to fine-grained, marly horizons of the Wellenkalk-Facies in the Muschelkalk. Historically, Querplattung have been attributed to soft-sediment deformation during seismic events, resulting in liquefaction and extension of water saturated horizons. Querplattung appear as unidirectional and bidirectional planar features with a normal sense of movement, separated by pressure solution seams and occasionally filled with clay-rich apophyses. Local displacements of 0.5-5mm are depicted along the intersection between bedding and highly oblique (270/57), high-aspect ratio, regularly spaced blocks. Studies show that Querplattung may exhibit brittle and ductile deformation structures ranging from horsetail-splays, dissolution seams and micro-faults to folded Querplattung (Neuweiler et al. 1999, Föhlisch & Voigt 2001). Folded Querplattung appear as sigmoidal or chevron shaped structures. Stylolites and slickolites are oriented subparallel and oblique to Querplattung surfaces. Preserved bioturbation and vertical compaction surfaces suggest horizons were shallowly buried during Querplattung deformation. Previous works have therefore suggested a specific rheological state and trigger is required for Querplattung formation (Neuweiler et al. 1999).

Geometric and structural analysis of Querplattung in the Thuringia Basin were conducted at outcrop and microscopic scale to understand their deformation process and possible importance for paleo-seismic analysis. Field measurements of Querplattung orientation correspond to those found in literature; suggesting the intersection of Querplattung strike lines and bedding are concentrically distributed around graben structures along the northern Tethys margin. Data comparison with pre-existing literature and isopach maps indicate that Querplattung orientation is not influenced by basin topography, also not contradicting a seismic origin. Thin-section microscopy and digital image analysis of $\mu$XRF element maps show that clay-rich material flowed into dilatant sites at the edges of individual blocks. Block rotation is traceable along rotated bedding, indicated by compositional variations. Pressure solution seams overprint all structures and cannot entirely account for the observed block rotation and marker offset.

We suggest these features represent brittle structures formed in fluid saturated, unconsolidated sediments caused by seismic wave propagation. Brittle failure of soft sediments can be achieved by strain hardening due to dilatancy. To accommodate raised shear stress, trapped pore-water becomes more viscous during slip along grain contacts (Buckingham 2000). Fracture orientation and dip-slip are spatially related to the propagation direction of seismic waves, suggesting wave coupled shear stress resulted in failure. Concomitant dewatering of the fractured sediment layer results in a net volume decrease. Stretching of the affected horizon manifested by en-echelon normal faults resulting in "Querplattung" does not reflect extension of the underlying crust. As seismically induced strain rate decreases, ductile deformation partially overprints the syn-seismic fractures. We therefore interpret the Querplattung as a seismically induced, intrastratal, synsedimentary analogue of the "bookshelf-mechanism".

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# Geology and Structure of the Spitskop Volcanic Centre, Rosh Pinah Mine, Southern Gariep Belt, Namibia

W.P. Colliston[a], Christoph Gauert[b]

[a]University of the Free State, South Africa, [b]Landesamt für Geologie und Bergwesen Sachsen-Anhalt, Germany

This study of the economic potential of the deformed Spitskop volcanics north of Rosh Pinah in Southernmost Namibia provides a structural framework for the understanding of effects of Late Proterozoic/Early Palaeozoic Gariep Belt tectonics, and of the stratigraphy of the bi-modal Spitskop volcanics and associated volcano-sedimentary units. The dominant features of the Gariepean tectonics identified in the project area are:

- A series of map scale nappe and sheath-fold nappes, and isoclinal folds.
- Thrust faults separate the nappes.
- All megascopic structures verge to the southwest; the Mesoproterozoic Namaqua Basement overthrusts the Spitskop volcanics.
- The thrusts and nappes have been deformed by a mainly southeasterly strike-slip sinistral shear along their boundaries and within folded banding; this gives an anastomosing appearance to the deformed structures.
- Fold axes of the various phases as well as the long-axes of sheath folds are coaxial and predominantly plunge shallowly to the northwest, indicating a tectonic transport direction to the southeast.

The structural interpretation deduced from the regional and local nature and kinematics of the structures mapped is that of a model of progressive differential ductile movement in a thrust regime; the large-scale regional thrusting and nappe emplacement takes place towards the Mesoproterozoic Namaqua Metamorphic Complex foreland in the southeast. In order to explain the difference in tectonic transport between the regional southeasterly thrusting direction and the southwestern Spitskop area, recourse to the regional model is necessary.

The northeast margin of the Gariep arc with the Namaqua Basement represents an oblique to lateral ramp. The oblique differential displacement along the ramp gives rise to rotation of D1 nappes and thrusts through the vertical to dip steeply northeastwards, as well as compression, producing the southwestwards overthrusting of the Namaqua Basement onto the D1 nappes. The Aus Road Fault zone from Rosh Pinah to north of Spitskop demarcates the area of dip reversal that is associated with this progressive rotational and compressive event (D2). Superimposed onto the D2 rotation is a D3 strike slip shear, which is a regional phenomenon.

The stratigraphy deduced from the structural-stratigraphic sections and in-fill mapping is based upon the structural framework developed. The stratigraphy of the project area has been subdivided into a structural stratigraphy confined to the dominant nappes identified and restored to D2 namely, the Rosh Pinah, Pisbos, VMU (volcanoclastic marker unit - tuffaceous sandstone with interbanded carbonate and iron formation (TsCG) units), Waterfall and Kudu sheath fold nappes. The Rosh Pinah Nappe comprises only part of the project area and the status of the structure – nappe only or fold-nappe, remains to be determined. If the fold nappes are restored to D1, then it is deduced that the structural age of the nappes would be from Rosh Pinah (oldest) to Kudu (youngest). Since the nappes control the distribution of the stratigraphic units regionally and locally in the Eastern Gariep Belt, the spatial distribution of Zn-Pb-(Ag,Ba,Cu) deposits is also structurally controlled; the understanding of the tectonics of the region is a critical forward step in modeling the economic potential of the base-metal province.

# Geoscientific Research at BASE – Activities to Enhance Understanding of Safety Relevant Aspects for the Disposal Site for High Level Radioactive Waste

Carlo Dietl, Christoph Borkel

Federal Office for the Safety of Nuclear Waste Management (BASE), Germany

The Federal Office for the Safety of Nuclear Waste Management (BASE) is the supervising authority for the site selection process for a deep geological repository for high-level radioactive waste (HAW) in Germany. Performing research in its areas of responsibility is a mandatory task for BASE. For this reason an Research Department was built up within BASE from the beginning on. Since HAW will be stored within a deep geological repository, geosciences are a key discipline in the search for the site with the best possible safety. However, research for a deep geological repository for HAW includes scientific, technical and non-technical aspects, i.e. it encompasses all possible aspects from long term safety of the disposal site to participation of the public in the site selection process. Consequently, research is interdisciplinary and involves natural sciences as well as humanities. BASE published its first research strategy (`www.base.bund.de/SharedDocs/Downloads/BASE/DE/broschueren/bfe/forschungsstrategie_final.html`) and research agenda (`www.base.bund.de/SharedDocs/Downloads/BASE/DE/broschueren/bfe/forschungsagenda_final.html`) in 2019 where the key aspects of research activities are laid down. Research projects investigated, e.g., knowledge about active fault zones in Germany and investigated possibilities of fluid percolation within rock salt under relevant p/T-conditions. Ongoing projects investigate, e.g., the protection function of the overburden of the containment-providing rock zone, the impact of changing climatic and tectonic conditions on hydrogeological systems and radionuclide transport or the potential alternative solutions to deep geological disposal of HAW.

Besides classical in-house as well extramural research projects, BASE engages in several projects at the underground research laboratories 'Grimsel Test Site' (crystalline rock) and 'Mt. Terri project' (clay rock) as well as in the international numerical modelling initiative DECOVALEX. At Grimsel BASE is involved, for example, in an experiment, which investigates the mobility of radionuclides in crystalline rock. In Mt. Terri BASE takes part, e.g., in experiments related to gas transport in claystone and the effect of physical deformation on the isotopic signatures of clay minerals. Participation in the DECOVALEX initiative is aimed to deepen our understanding for thermo-hydro-mechanically coupled processes in repository systems consisting of host rock, geotechnical barriers and waste containers with relevance for performance assessment studies. BASE is interested in spreading its research topics into communities which may contribute, but still are not aware of these topics and it supports future expert generations, e.g. by establishing its own PhD-program in collaboration with universities.

# Western Pamir Tectonic evolution constrained by paleomagnetic and provenance data

Guillaume Dupont-Nivet[a,b], Lin Li, Jovid Aminov, Pierrick Roperch, Yani Najman
[a]CNRS - Géosciences Rennes, France, [b]Potsdam University, Germany

The tectonic history of the Pamir contributes to our understanding of both the evolution of collisional orogenic belts as well as factors controlling the Central Asian aridification. However, how and when the Pamir formed remains an open question. We explore here Pamir tectonics recorded in a sedimentary section in the eastern Tajik Basin that was dated with magnetostratigraphy. New detrital apatite and zircon fission-track (FT) ages recorded in the section and Pamir modern river sands, in compilation with published detrital fission-track data from the adjacent Tarim Basin, reveal the Mesozoic–Cenozoic tectonic history of Pamir. The data also show significant Cenozoic exhumation in the Pamir with three sub-stages: late Oligocene–early Miocene (27–23 Ma), middle–late Miocene (15–10 Ma), and late Miocene (7.5 Ma), which presumably lead to the formation of the present Pamir. The combined analysis of vertical-axis rotation and magnetostratigraphic dating yields strong counterclockwise rotations ($\sim 56°$) in early Late Cretaceous to late Miocene strata. This result suggests that rotation in the Tajik Basin occurred after 8 Ma, much later than previously suggested. Combining with a regional compilation of previous paleomagnetic studies as well as structural and GPS constraints including Pamir and Tarim, we explore potential implications on models of the Pamir salient. We infer that after 8 Ma, the Pamir (North, Central, and South) began to overthrust west- and northwest-ward, causing counterclockwise rotations in the Tajik Basin. This reconstruction allows for $\sim$ 150 km of post-8 Ma northwestward indentation into the Tajik Basin, in agreement with coeval underthrusting of the Indian mantle lithosphere into Asia.

# Stress orientation indicators in Chicxulub's peak ring

Matthias Ebert, Michael H. Poelchau, Thomas Kenkmann
Albert-Ludwigs-Universität Freiburg, Germany

During meteorite impacts, target rocks are subjected to high mean shock pressures as well as high differential stresses. These differential stresses cause microscale shear deformation, which occur in the form of kinking, twinning, fracturing and shear faulting of a range of minerals. The orientation of these microstructures can be used to constrain the maximum shortening axis. Under the assumption of pure shear deformation, the maximum shortening axis is parallel to the maximum principal axis of stress, $\sigma1$, which gives the propagation direction of the shock wave that passed through a rock sample during a hypervelocity impact. Shear deformation microstructures that constrain shock wave orientation and propagation in target lithologies can thus provide valuable new insights into the cratering process. In this study, we investigated the orientation of planar microstructures in biotite and quartz of the cored peak ring granitoids of the Chicxulub crater from IODP/ICDP Expedition 364, using the hypothesis that these shock indicators form along directions that show a preferred orientation regarding shock wave propagation direction. We used kink bands in biotite to derive a set of local $\sigma1$ principal axis of stress orientations, thus documenting the three-dimensional configuration of principal stress directions in the peak-ring granites during shock pressure. We then benchmarked this against $\sigma1$ data from feather feature orientations in quartz. Feather features are a further shock-derived microstructure that consist of a planar fracture and a set of lamellae that emanate in one direction of the planar fracture at an angle $> 35°$. They form when planar fractures are activated as shear planes (Poelchau & Kenkmann 2011, Ebert et al. 2020). Poelchau & Kenkmann (2011) observed that feather feature lamellae point in the direction from which the shock wave came, thus, they also constrain the orientation of the principal axis of maximum stress, $\sigma1$. Furthermore, we determined the spatial orientation of basal planar deformations features (PDFs) in quartz relative to derived $\sigma1$ orientations. In all three cases the orientations were measured with a Universal-stage microscope. The $\sigma1$ orientations derived from these measurements are in good agreement with each other, showing that the shear deformation features all formed under approximately the same stress field within the shock wave. These shear-induced deformation features are useful tools that can aid in understanding the detailed effects of shock wave deformation, as well as constraining shock wave propagation and post-shock deformation of the cratering process. However, it is important to know the exact deformation conditions since the path of shock metamorphism depends on the position of the material relative to the point of impact (Rae et al. 2021). In the case of the Chicxulub impact structure, the analysis within this study supports the hypothesis that peak ring material undergoes large rotations during peak ring formation.

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# Ice tectonics on Jupiter´s moon Ganymede: Kinematic restoration of dark terrains

Max Fabi[a], Thomas Kenkmann[a], Gerwin Wulf, Namitha R. Baby[b], Katrin Stephan, Roland Wagner

[a]Albert-Ludwigs-Universität Freiburg, Germany, [b]Institute of Planetary Research, DLR, Berlin, Germany

Ganymede – the largest moon in the solar system, bigger than planet Mercury – has a crust composed of ice with a layer of saltwater underneath and a rock-ice interior. Its surface can be subdivided into dark and light terrain [1]. The dark terrain covers about one third of the surface, is composed of relatively low albedo material (ice & dust) and has a high crater density. The two third light terrain is characterized by higher albedo and a lower crater density indicating a relatively younger age [2]. Its surface is sculptured by grooves and ridges that suggest a more recent activity of this terrain with respect to the dark terrain. The assemblage of lineated grooves has been interpreted as extensional zones similar to the Earth continental rifts [3]. Neighboring dark terrains often show fitting pattern, indicating that the areas have drifted apart by extension. Here, we reconstruct magnitude and orientation of the finite extension between adjacent dark terrains. The kinematic restoration allows to better understand the global tectonic movement pattern and may ultimately help to answer the question whether the individual dark terrains once formed a single terrain that covered the entire, formerly smaller moon surface.

We used the global Ganymede image mosaic of Voyager 1 and 2 and Galileo images [4-6]. Using ESRI's ArcMap 10.7 software polygons of all dark terrains were created in accordance to existing geological mappings [1]. During the process of translating and rotating dark terrain polygons, there is the fundamental problem of distortion according to the projection in use. We have solved this by centering the projections on the polygon groups to be moved. The relative movement and translation vectors were centered to the midpoint of each dark terrain polygon. The resulting vectors represent magnitude and direction of the extension of dark terrains since its presumed break-up. We will show results of the tectonic restoration of the dark terrain. The closure of smaller rift zones was the initial step in our restoration. Based on visible fitting pattern between the larger dark terrains, eventually a "super dark terrain" was compiled. The majority of reconstructed vectors radiate away from each other. This suggests an expansion of the moon after the formation of the dark terrain. Movements deviating from this pattern indicate intrinsic forces. At present, our reconstruction gives no indication of the timing of rifting. The reconstructed translation vector field is to be understood as a relative vector field, since an absolute reference system is missing. Due to the uneven spatial resolution of the available data, reconstructions are vague in some areas. The planned JUICE mission [7] will remedy this situation.

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## Deformation fabrics of the Neoproterozoic Rothstein Formation in southern Saxony-Anhalt

Gregor Facius[a], Bodo-Carlo Ehling[b], Michael Stipp[a]

[a]Martin-Luther-Universität Halle-Wittenberg, Germany, [b]Landesamt für Geologie und Bergwesen, Sachsen-Anhalt, Germany

The geological cover of the state of Saxony-Anhalt is characterized by a block-tectonic deformation pattern caused by Cretaceous to Paleogene intraplate tectonics. The Bitterfeld horst of the Wolfen block is in a tectontically elevated position, bounded by the NW-SE-striking Gräfenhainichen fault in the NE and the Köthen-Bitterfeld fault in the SW. Consequently, the Bitterfeld horst contains older stratigraphic formations in comparison to the surrounding blocks that are at or close to the surface. This allows to study the transition between the Mid-German Crystalline Zone and the Southern Phyllite Zone of the Variscan basement that is exposed in several drill cores from the border region between the states of Saxony-Anhalt and Saxony south of Bitterfeld. The borehole Wis BAW 1316/79 is located at the northern margin of the Southern Phyllite Zone that contains the Neoproterozoic Rothstein Formation with an apparent thickness of 365.6 meters. The formation is of significantly higher metamorphic grade than the Neoproterozoic rocks located further south between Delitzsch and Leipzig, probably indicating a structural pile-up at the tectonic boundary to the Mid-German Crystalline Zone. The turbiditic greywackes to mudstones of the Rothstein Formation largely resemble the sequence described by Buschmann et al. (2006) in the so-called Torgau-Doberlug syncline. The Rothstein Formation of the Bitterfeld horst is overlain by strongly weathered sediments of the Mansfeld Supergroup.

The description of the lithologies as well as their deformation characteristics was done by thin section analysis using light-optical microscopy. Lithologically, the Rothstein Formation represents siltstones, greywackes, turbiditic siltstones and strongly altered volcanic rocks that are overprinted by anchimetamorphic to lower greenschist facies metamorphic conditions. The sedimentary rocks of shallower depth are non-metamorphic to anchimetamorphic and brittlely deformed. Characteristic are brittle shear band structures, boudinage and layer-parallel fractures and faults. Below a depth of 474.30 m, lower greenschist facies siltstones occur, which display a strata-parallel pressure-solution foliation, small folds, crenulation cleavage and shear bands. Quartz microstructures show intragranular deformation features like undulose and patchy extinction, serrated grain boundaries as well as bulges indicative of incipient crystal plastic deformation. In contrast, the volcanic rocks show only a few brittle deformation features.

Overall, deformation by strata-parallel thinning and metamorphic overprinting is interpreted as setting of Variscan accretion and subduction metamorphism. The metamorphic step from barely metamorphic and brittlely deformed to lower greenschist facies and viscously deformed rocks of the Rothstein Formation at 474.30 m is thought to be a result of Permian or Mesozoic extensional tectonics.

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# The Beni Bousera marbles: witnesses of the early exhumation of granulites and peridotites of the Rifan internal zone (Rif Belt, Morocco)

A. Farah[a], M. Corsini[b], O. Saddiqi[a], A. Michard[c], C. Chopin[d], P. Montero[e], A. Chalouan[f], F. Bea[e]

[a]Hassan II University, Casablanca, Morocco, [b]Université Côte d'Azur, CNRS, Sophia Antipolis, France, [c]Université Paris-Sud (Orsay), Paris, France, [d]Université PSL, Paris, France, [e]University of Granada, Spain, [f]Mohamed V University, Rabat-Agdal, Morocco

The Gibraltar arc is famous for its subcontinental peridotites that extend widely in Spain (Ronda) and Morocco (Beni Bousera). The timing and processes of the exhumation of these mantle rocks are still a matter of controversy. We contribute to this debate through a multi-scale and multidisciplinary study of high-grade marbles outcropping around in the Beni Bousera antiform (northern Rif). New field investigations show that these Beni Bousera marbles (BBMs) form lenticular outcrops, $\sim$ 30 to 300 m thick, located between the granulates (kinzigites) of the Beni Bousera Unit (BBU) and the gneisses of the overlying Filali unit. These calcite-dolomite marbles present silicate-rich levels with conglomeratic layers that rework the peridotites. The structural analysis shows that the BBMs punctuate a major ductile shear zone: the Filali-Beni Bousera Shear Zone (FBBSZ), marked by intense mylonitization. The FBBSZ is accompanied by nested thrusts that place the kinzigites on the marbles with NW kinematics characterized by NNE-trending fold axes. Late normal faults cut the ductile structures of the FBBSZ. The petrological study shows that the BBMs did not underwent the HP-HT metamorphism of Variscan age recorded by the underlying granulites, but rather a HT-LP metamorphism ($\sim 700-750$ °C, 4-8 kbar) comparable to that of the overlying Filali gneiss unit. U-Th-Pb geochronological analyses indicate that detrital zircon cores from the BBMs yield two age groups at $\sim$ 270 Ma and $\sim$ 340 Ma, which suggests a post-Permian depositional age. The zircon rims provide ages at $\sim$ 21 Ma, corresponding to the back-arc opening of the Alboran Basin. $Ar^{40}/Ar^{39}$ phlogopite dating of the BBMs provided ages between 23 Ma and 24 Ma that we attribute to the setting of the FBBSZ under conditions of HT-LP metamorphism, related to the emplacement of gneisses of Filali Unit on kinzigites and peridotites of the BBU. These results indicate that the Beni Bousera mantle rocks were exhumed at shallow depths as part of the southern hyper-extended margin of the Alboran domain during the Triassic-early Jurassic rifting responsible for the birth of the Maghreb Tethys. During the Alpine orogeny, the BBU, the BBMs, and the Filali unit were affected during the Oligocene by tectonic burial in a HT-LP metamorphic context, before their final exhumation on the Miocene.

# Microstructural Evolution of Fertile Lithospheric Mantle During Rift Initiation

Ulrich Faul[a], Allison Seyler, Gordana Garapic
[a]MIT, MA, USA

The Krivaja-Konjuh massif in central Bosnia is one of the largest peridotite complexes within the Dinaride ophiolite belt with an area of 650 km$^2$. The massif consists predominantly of spinel lherzolites that were locally highly deformed. High $Na_2O$ contents in clinopyroxene (cpx) together with spinel-orthopyroxene (opx) symplectites after garnet indicate a relatively high pressure, subcontinental origin of the western and southern parts of the massif, similar to orogenic massifs such as Lherz and Lanzo. Compositions from the eastern part (Konjuh) are somewhat more depleted and indicate lower pressure, possibly a mid-ocean ridge related origin. Together with the occurrence of ophicalcites and cherts, indicative of a deep water origin, the massif likely represents an ocean-continent transition.

The mantle portion of the Krivaja massif consists predominantly of spinel peridotite, with plagioclase peridotite occurring locally indicating impregnation by melt. In comparison to the more extensively studied Alpine and western Mediterranean massifs the western-most Dinarides, including the Krivaja massif are fertile, containing 10 - 15 % clinopyroxene. Rare earth element patterns of cpx from spinel peridotites show slight depletion, but importantly no refertilization - in contrast for example to Lherz. The spinel peridotites throughout the massif show variable degrees of deformation. The least deformed samples indicate pre-deformation grain sizes near 1 cm, the most highly deformed samples are mylonytic/ultramylonitic with grain sizes around 50 micron. This range of deformation grades in different parts of the massif enables examination of progressive grain size reduction due to recrystallization.

Pyroxene porphyroclasts have exsolution lamellae in their cores. These cores represent a record of equilibration prior to the onset of deformation. In order to estimate temperatures prior to exsolution, area maps of grain cores are obtained, which integrate to pre-exsolution compositions. Two-pyroxene thermometry of the integrated cores indicates temperatures at the onset of deformation in excess of 1300 °C, suggesting that at least part of the massif originates at asthenospheric conditions, consistent with its fertile nature. The lowest calculated temperatures from some of the most deformed samples show a record of increasingly intense deformation at decreasing temperatures.

The relative strength of the three major phases olivine, opx and cpx can be inferred from grain shapes and degree of recrystallization of each phase. Opx is typically the strongest phase, and in some cases rotates as rigid clasts. Cpx is in some samples elongated to aspect ratios $> 20 : 1$, in others completely recrystallized, similar to olivine. In some samples opx is stretched and begins to recrystallize, while some olivine grains remain porphyroclastic.

The massif may therefore represent a record of deformation initially in the absence of melt or significant water contents (no hydrous phases are observed). It records continental break-up, with deformation starting at high temperatures at or beneath the lithosphere-asthenosphere boundary, and continuing down temperature during lithospheric thinning and the onset of decompression melting, melt segregation and formation of an incipient ocean basin.

## Post-Variscan Rotliegend basins in SE Germany and their regional context as revealed by seismic reflection and potential field data

Hamed Fazlikhani, Wolfgang Bauer, Harald Stollhofen, Johannes Wiest, Daniel Koehn
Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

Late-Carboniferous – Permian sedimentary rocks of the Rotliegend group are exposed in SE Germany in the footwall and hangingwall of the Franconian Fault System (FFS) in several isolated occurrences. In addition, west of the FFS, several wells encountered Rotliegend units, and show rapid thickness and facies changes. Based on outcrop and well observations, Rotliegend basins in northeastern Bavaria (SE Germany) are traditionally interpreted as relatively small (tens of km) and isolated NW-SE striking fault-bounded basins and compartments of the more extensive SW-NE Kraichgau Basin. However, lack of outcrop and limited well data obscure a better understanding of basin architecture and their possible connectivity.

In this study we integrate surface geological and well data with seismic reflection, gravity and magnetic data to investigate the architecture of Rotliegend basins in northern Bavaria. The recently acquired Franken 2D seismic survey and reprocessed KTB and Oberpfalz profiles are tied to available wells. Seismic reflection data image the basin architecture and are used to estimate remnant thicknesses of Rotliegend units. In the absence of well and seismic reflection data, filtered Bouguer gravity and magnetic data show the location of possible Rotliegend basins covered by uppermost Permian and Mesozoic sedimentary rocks of the Franconian Basin. In contrast to the fault-bounded Rotliegend basins, the Franconian Basin is largely characterized by the absence of syn-depositional faults. The post-depositional structural architecture of the Franconian Basin is dominated by sub-parallel NW-SE striking thrust faults such as the Eisfeld-Kulmbach and Lichtenfels faults.

Based on the seismic facies of drilled Rotliegend rocks, we interpret the presence of several un-drilled and fault bounded Rotliegend basins along the FRANKEN seismic survey. However, the lower boundary of these Rotliegend basins is tentative and cannot always be clearly identified. Farther SE, Oberpfalz and KTB seismic reflection data were reprocessed and spectacularly image the architecture of the Naab Rotliegend Basin. We show that the Naab Basin stores ca. 3000 m thick Rotliegend strata, 300-500 m thicker than previously reported. Integration of filtered gravity and magnetic data with seismic reflection data further images the lateral extension of Rotliegend basins. We show that Rotliegend basins are mainly bounded by E and ENE dipping normal faults. Our analysis and interpretation show that late Mesozoic and Cenozoic tectonic activities selectively reactivate E and ENE dipping structures manifested as Rotliegend exposures.

# The Lower Juvavic of the Eastern Alps: Tectonic mélange or salt-controlled carbonate deposition?

Oscar Fernandez[a], Bernhard Grasemann[a], Hugo Ortner[b], Thomas Leitner[c]
[a]Universität Wien, Austria, [b]University of Innsbruck, Austria, [c]Salinen Austria AG, Austria

The Northern Calcareous Alps (NCA) of the Eastern Alps are traditionally subdivided into three main thrust units, from bottom (north) to top (south): Bajuvaric, Tirolic and Juvavic. The Juvavic unit is in turn subdivided into the upper and lower Juvavic units. The lower Juvavic unit is characterized by a highly condensed Middle to Late Triassic carbonate stratigraphy (Hallstätter facies), at most a few 100s of meters, deposited in deep water (100s of meters depth). In contrast, the time equivalent stratigraphy of the Tirolic and upper Juvavic units is dominated by shallow water (lagoonal and reefal) carbonates. Lower Juvavic Hallstätter facies are frequently found in association with Permian-age evaporites and lying over Jurassic rocks of the Tirolic or upper Juvavic. Permian evaporites crop out in the NCA almost exclusively in connection with lower Juvavic outrcrops.

The outcrops of the lower Juvavic unit typically form semi-circular or elongate shapes in map view often lie in allochthonous position lying on the upper Juvavic and Tirolic units. Within outcrops of the lower Juvavic, the Triassic Hallstätter facies are observed to vary rapidly laterally. This arrangement in combination with the contrast in Triassic depositional environments between the lower Juvavic and the upper Juvavic and Tirolic units, has been conventionally interpreted to result from the gravitational emplacement of the lower Juvavic as olistoliths (by gravitational gliding: Gleittektonik) in the Middle to Late Jurassic prior to the onset of Eo-Alpine tectonism.

In this presentation we will explore the arrangement and structure of lower Juvavic outcrops in the region of the central NCA and discuss the possibility that at least part of the observed lateral variations and arrangement of Triassic facies can actually be explained by the depositional architecture of carbonates above growing diapirs. Two sectors will be discussed in particular, where evidence for the deposition of the Hallstätter facies above salt structures is most evident. Salt-related deposition as described at these locations might provide an alternative explanation for some of the observations that are used to defend the gravitational emplacement of the lower Juvavic unit.

One is the sector of Bad Goisern – Altaussee, where the lower Juvavic rests on the Tirolic unit. In this area Triassic units are found arranged in concentric facies rings, a geometry interpreted to represent the original facies distribution as they deposited atop a growing diapir, without having experienced the dismemberment expected of gravitational emplacement.

The second region is that of the southwestern margin of the Dachstein Massif (the Gosaukamm) where the shallow water Triassic of the upper Juvavic transitions into the Triassic of the Hallstätter domain in its presumed original location. Sedimentary and structural geometries in this transition zone could be explained by the presence of a Triassic-age salt wall under the domain of Hallstätter facies. This region is of particular relevance as it is the southernmost end of the Lammer Zone, one of the most areally extensive lower Juvavic outcrops in the NCA and one where the allochthonous nature of the lower Juvavic units has been best documented.

## The role of grain boundaries for the deformation and grain growth of olivine at upper mantle conditions

Filippe Ferreira[a], Marcel Thielmann[b], Katharina Marquardt[c]

[a]University of Heidelberg, Germany, [b]Universität Bayreuth, Germany, [c]Imperial College London, Great Britain

Crystal defects such as vacancies, dislocations and grain boundaries are central in controlling the rheology of the Earth's upper mantle. Their presence influences element diffusion, plastic deformation and grain growth, which are the main microphysical processes controlling mass transfer in the Earth's lithosphere and asthenosphere. Although substantial information exists on these processes, there is a general lack of data on how these defects interact at conditions found in the Earth's interior. A better understanding of processes occurring at the grain scale is necessary for increased confidence in extrapolating from laboratory length and time scales to those of the Earth. We examined the evolution of olivine grain boundaries during experimental deformation and their impact on deformation in the dislocation-accommodated grain- boundary sliding (disGBS) regime. This may be the main deformation mechanism for olivine in most of Earth's upper mantle. Our results suggest that grain boundaries play a major role in moderating deformation in the disGBS regime. We present observational evidence that the rate of deformation is controlled by assimilation of dislocations into grain boundaries. We also demonstrate that the ability for dislocations to transmit across olivine grain boundaries evolves with increasing deformation. Lastly, we show that dynamic recrystallization of olivine creates specific grain boundaries, which are modified as deformation progresses. This might affect electrical conductivity and seismic attenuation in the upper mantle. The effective contribution of grain-boundary processes (such as disGBS) on the rheology of the upper mantle is correlated to the amount of grain boundaries in upper mantle rocks, that is, their grain-size distribution and evolution. The grain-size distribution in the Earth's mantle is controlled by the balance between damage (recrystallization under a stress field) and healing (grain growth) processes. However, grain growth, one of the main processes controlling grain size, is still poorly constrained for olivine at conditions of the upper mantle. To evaluate the effects of pressure on grain growth of olivine, we performed grain growth experiments at pressures ranging from 1 to 12 GPa using piston-cylinder and multi-anvil apparatuses. We found that the olivine grain-growth rate is reduced as pressure increases. Our results suggest that grain-boundary diffusion is the main process of grain growth at high pressure. Based on extrapolation of our experimental results to geological time scales, we suggest that at deep upper-mantle conditions (depths of 200 to 410 km), the effect of pressure on inhibiting grain growth counteracts the effect of increasing temperature. We present estimations of viscosity as a function of depth considering the grain-size evolution predicted here. Our estimations suggest that viscosity is almost constant at the deep upper mantle, which corroborates postglacial-rebound observations.

# Structural geological study of a shear zone at the Stora Le Marstrand Formation, SW Sweden

Anna Friebel, Thomas Degen
Martin-Luther-Universität Halle-Wittenberg, Germany

The geology in SW Sweden is strongly influenced by the sveconorwegian (1.1-0.9 Ga) and gothain orogeny (1.7-1.5 Ga). During these deformational events the Idefjorden Terrain was aggregated on the Baltic Shield and large crustal units had been sheared and stacked on each other. These crustal units are built up mainly of meta-sediments (ca. 1.67 Ga) which had been intruded by several magmatic suits (1.5-0.9 Ga) of felsic as well as mafic to ultramafic compositions (Stephens, 2020). The main topic of research is a vertical dipping N-S trending shear zone which is located on the small isle Arndorsholmen close to Lökeberg. As part of the field work Arndorsholmen was photographed from above with a mini drone. With help of the obtained images a textured 3D model of the topography was modelled and highlights the structure of the shear zone perfectly. Additionally, the detailed analysis of the shear zone gives indications of various deformational and metamorphic overprints. So, the rocks are highly overprinted by metamorphism and great displacement as a result of the orogeny have taken place. This study aims to model different deformational periods of this area by tectonic data and cross sections. Furthermore the different lithologies are analysed microscopically with special focus on shear sense indicators and stretching lineation. Finally, the grade of metamorphism was determined to reconstruct the p-T-conditions during this deformation.

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# From Tiefencastel to Thurnstein: Vestiges of a sinistrally transpressive shear zone of Late Cretaceous age in the Austroalpine Nappes

Nikolaus Froitzheim, Simon Fuhrmann, Linus Klug, Pia Schneider
University of Bonn, Germany

The Austroalpine Nappes west of the Tauern Window and south of the Northern Calcareous Alps were stacked by mostly northwest-directed thrusts during the Cretaceous, starting around 100 Ma ("Trupchun A" deformation phase; Froitzheim et al., 1994, Eclogae Geol. Helv. 87, 559-612). Along the southern border of the Silvretta Nappe in Graubünden, an east-west-trending steep zone occurs (Albula Steep Zone) where the Lower Austroalpine nappes of the Bernina system have been folded into tight, E-W-trending, upright folds during the "Trupchun B" phase. Trupchun A folds of the Silvretta Nappe are dragged counterclockwise in map view when approaching the Albula Steep Zone. Therefore, this zone is interpreted as a sinistrally transpressive shear zone. The upright folds interfere with younger, recumbent "collapse folds" and top-southeast normal faults, both related to the Ducan-Ela Phase of crustal extension which took place in the area at $\sim$ 80 to 67 Ma.

Further east, the continuation of the Albula Steep Zone beyond the younger, Tertiary-age Engadine Line is probably hidden under the Quattervals Nappe of the Engadine Dolomites. The units underlying the Quattervals Nappe to the South and to the North exhibit different facies and tectonic style, which could be explained by a hidden strike-slip shear zone. We suggest that this shear zone re-emerges still further east in the Vinschgau Valley. The belt of greenschist-facies mylonites on the northern side of the Vinschgau Valley, known as the Vinschgau Shear Zone, has been identified as the basal thrust along which the Ötztal Nappe moved westward over the Campo Nappe cropping out south of the valley (Schmid & Haas, 1989, Tectonics 8, 697-718). Our new field study of the Vinschgau Shear Zone between Schlanders and the Schnals Valley yielded the following results: (1) The mylonitic foliation dips mainly north but locally also south; (2) two generations of folds deform the foliation; (3) folds of the younger, dominant generation have shallowly-dipping to subhorizontal axial planes; (4) in some places, the orientation of the foliation changes from north-dipping to south-dipping around recumbent fold hinges; (5) the shear sense is predominantly top-west (62%) but top-east shear sense also occurs in many places (38%). Our interpretation is the following: These mylonites indeed represent the basal top-west shear zone of the Ötztal Nappe, intensely deformed and reoriented by initially upright Trupchun-B folds (in a framework of sinistral transpression) and recumbent Ducan-Ela-phase "collapse folds". Top-east mylonites represent (at least partly) original top-west mylonites reoriented by folding.

In a recent paper (Klug & Froitzheim, 2021, Int. J. Earth Sci., doi: 0.1007/s00531-021-02127-4) we presented evidence that towards east, the Vinschgau Shear Zone does not turn northeast to separate the Ötztal Nappe from the Texel Complex, as suggested by some authors. Instead, it continues under the Quaternary Vinschgau Valley fill and reappears at Thurnstein Castle near Meran. Taken together, this "Tiefencastel-Thurnstein Line" represents a 120 km long, sinistrally transpressive shear zone of Late Cretaceous age, overprinting the Austroalpine nappe stack. Its large-scale tectonic framework is still uncertain.

# The mylonites of the Vinschgau Shear Zone between the Schnals Valley and Schlanders, South Tyrol

Simon Fuhrmann, Nikolaus Froitzheim
University of Bonn, Germany

Between the the Ötztal Alps and the Ortler Group in the northwest of South Tyrol, west of Meran, lies the broad west-east oriented Vinschgau valley. On the northern slope of this valley, various strongly deformed Variscan basement rocks are exposed, including orthogneisses, amphibolites and mica schists. In the western part, iron-carbonate-bearing schists occur which represent Permo-Triassic sediments. All of these rocks are partially mylonitized over large areas from the valley to the ridge between Schlanders and the Schnals Valley.

This shear zone has been considered to be the west-directed overthrust contact of the Ötztal nappe to the N over the Campo nappe to the S. The shear zone is reportedly dominated by top-W mylonites and continues towards east into a diffuse, strongly folded zone which turns NE and runs along the NW margin of the Texel Complex (Schmid & Haas 1989). Structural analysis of the Vinschgau Shear Zone between the Schnals Valley and Schlanders was conducted in order to understand the tectonic evolution of the area in more detail. For this purpose, we measured foliation, stretching lineation, fold axes and fold axial planes in the field and documented outcrop-scale shear-sense criteria. Thin sections parallel to the stretching lineation were made from oriented samples to determine the shear senses on a small scale.

The shear zone shows both north- and (minor) south-dipping foliation, west-east directed stretching lineation and folds with subhorizontal to shallow, often N to NW-dipping axial planes. The mylonites show both top-W and top-E shear senses. Both shear senses occur in rocks with south-dipping as well as in rocks north-dipping foliation. At Juval, at the entrance to the Schnals Valley, we found particularly well-developed mylonites to the South of and outside the shear zone mapped by Schmid & Haas (1989). Mineral parageneses and quartz microstructures suggest most rocks were metamorphosed in the amphibolite-facies and subsequently mylonitized in the greenschist-facies.

In conclusion, the Vinschgau Shear Zone shows a complex structure that indicates an equally complex history. The different shear senses suggest two phases but need to be further evaluated. In addition, we consider at least part of the Vinschgau Shear Zone to continue eastwards through the valley towards Meran.

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# Screening the landscape signal of active tectonics in the Klagenfurt Basin, Eastern Alps (Austria)

Christoph Grützner[a], Mark Mücklisch[a], Erick Prince[a], Klaus Reicherter[b], Sumiko Tsukamoto[c], Kamil Ustaszewski[a]

[a]Friedrich-Schiller-Universität Jena, Germany, [b]RWTH Aachen, Germany, [c]LIAG Hanover, Germany

In this study we address potentially active faults in the Klagenfurt Basin in the Eastern Alps. At the longitude of the Eastern Alps, Adria is moving northward with respect to stable Europe at about 3 mm/yr. Most of this convergence is taken up along the South Alpine Front in northern Italy and by the right-lateral Dinaric Fault System in western Slovenia. Geodetic data show that about 1 mm/yr of shortening is accommodated around the Karawanks by the Sava Fault and/or the Periadriatic Fault System, or by nearby faults. The Karawanks are bounded to the north by a thrust fault that separates them from the Klagenfurt Basin filled with Miocene and younger conglomerates. Within this basin, the east-west striking Sattnitz is an elongated hill also formed by Miocene conglomerates. It is bounded against the topographically lower, main part of the Klagenfurt Basin by a linear front that most likely represents a S-dipping thrust fault. Mining data show that Miocene coal seams are affected by faulting, and damaging historical earthquakes are proven for the study area. Therefore, the question arises if any faults in the Klagenfurt Basin are still active, or if the entire convergence is accommodated by the Sava-Periadriatic Fault System further south. The search for the landscape record of active faulting is complicated by the fact that the study area was glaciated during the Last Glacial Maximum (LGM) and previous glaciations. Thus, almost all landforms post-date the LGM. These young sediments and glacially induced surfaces combined with the very low deformation rates indicate that we cannot expect to find large offsets. However, 1 m resolution digital elevation models became available recently for the Austrian state of Carinthia. We expect that traces of active faulting postdating the LGM should be discernible as offsets within river terraces, alluvial fans, and other glacially induced or post-glacial geomorphic features. If there is no such signal, the deformation may be a) below resolution, b) have no vertical component, c) wiped out by anthropogenic actions, or d) the faults may be inactive. In cases (a) and (d) we can estimate an upper boundary for the maximum deformation rate that affects the Klagenfurt Basin. Here we report on remote sensing analyses, field work, and preliminary dating results. All our data indicate that the Sava-Periadriatic Fault System takes up most of the convergence, which is supported by observations from field work there. We discuss the implications for regional tectonics and the inherent uncertainties in such studies, which need to be accounted for when thinking about seismic hazard in the Alps.

# Structural record of the Late Cretaceous – Early Palaeogene regional tectonic compression in the Sudetes (NE margin of the Bohemian Massif)

Andrzej Głuszyński, Paweł Aleksandrowski
Polish Geological Institute, Poland

A brief review of the Late Cretaceous – Early Palaeogene inversion-related tectonic structures affecting the Sudetes and their foreland at NE margin of the Bohemian Massif is presented. The Sudetes expose Variscan-deformed basement, partly overlain by post-orogenic Permo-Mesozoic cover. The latter contains a wide spectrum of contractional tectonic structures. The largest in size are two regional-scale synclinoria: the North Sudetic and the Intra-Sudetic ones, extended in NW-SE direction. We used newly reprocessed oil-industry legacy reflection seismic data to study the internal structure of these two first-order units and extended our review with observations of structures of various size from mines and quarries distributed all-over the Sudetic area, as well as with critically assessed data from the literature. The tectonic structures produced in the post-Variscan cover of the Sudetes and the adjacent areas include gentle to moderate folds of buckling and fault-related origin, as well as high-angle reverse faults, some of them with strike-slip component. They include also low-angle thrusts, probably rooted in (older fractures in) the crystalline basement. The structures described as grabens by previous authors, are often bounded by reverse faults ('reverse grabens') and reveal strongly synclinal pattern of their sedimentary fill. The top of crystalline basement in the North Sudetic Synclinorium below the folded cover is synformally down-warped with a wavelength of up to 30 km, whereas on the elevated areas, where the top basement is exposed at the surface, it seems to be, similarly, up-warped (i.e. tectonically buckled). The reviewed compressional structures show, as a rule, an attitude (e.g. NW-SE trending strikes or axes) fitting the regionally-known orientation of the Late Cretaceous – Early Palaeogene tectonic shortening direction of NE-SW to NNE-SSW. The same applies to the regional joint pattern, typically comprising an orthogonal system of steep joints of NW-SE and NE-SW strikes. Some of the reviewed faults with strike-slip component of motion may have been also affected by a later, Late Cenozoic, tectonism.

# Orogenic Geothermal Systems: A Structural Geologist's Point of View

Marco Herwegh[a], Alfons Berger[a], Sandro Truttmann[a], Tobias Diehl[b]
[a]Universität Bern, Switzerland, [b]ETH Zürich, Switzerland

In the light of society's need for renewable energy, geothermal energy belongs to one of the pillars being in parts capable to replace fossil fuels. In contrast to rift-related hydrothermal cells with their significant thermal anomalies and high heat fluxes, gaining geothermal energy in orogenic systems might at a first glance appear less attractive. Based on examples from the Central European Alps, we demonstrate, however, that particularly transtensional domains within associated strike-slip fault systems can provide pathways that directly connect fluid flux from the lower upper crust up to the surface. Hence associated advective heat transport can produce substantial fault-bound positive thermal heat anomalies. Despite this vertical fluid flux over kilometers, the backside of the medal are the spatially strongly limited horizontal dimensions of related hydrothermal cells of a few hundred meters only. Using remote and field-based mapping, kinematic analysis and petrophysical fault rock characterization of exhumed hydrothermal cells we discuss where and why in such fault systems enhanced hydrothermal circulation has to be expected. The 3D geometry of the fault system's architecture, elevated recent crustal movements, critically stressed upper crustal faults as well as a high ratio of volumetric strain vs. fault healing capacity all provide ingredients being in favor for successfully establishing an orogenic hydrothermal cell. Besides exploitation of geothermal heat, a major gain would be the generation of electricity out of such a hydrothermal cell requiring fluid temperatures $> 120$ °C, i.e. target depths of 4-5 km. Consequently, reliable fault information at the target depth is mandatory prior to expensive drilling campaigns. Here we suggest a correlative workflow that combines surface information with a novel fault-plane imaging approach, based on which the 3D fault structure, its kinematics and fault segments being most prone for large volumetric strains can be evaluated from seismicity. In this way, the risk of finding suitable geothermal cells at depth can be reduced.

## Global challenges, subsurface reservoirs and structural diagenesis

Christoph Hilgers, Benjamin Busch, Dennis Quandt, Jasemin Ölmez, Felix Allgaier
Karlsruhe Institute of Technology - KIT & KIT Campus Transfer GmbH, Germany

Many global challenges are geology challenges. For example, the energy- and mobility transition will result in an increase of raw material demand and the utilization of the subsurface. This includes the long-term storage using CCS to achieve negative emissions, the safe disposal of nuclear waste, the interim storage of large renewable energy volumes in reutilized salt caverns as well as fractured and porous storage sites, the storage of heat and the exploration of geothermal energy. Reservoir characterization and reservoir quality prediction considers porosity loss due to cementation in pores, and the formation, persistence and cementation of fractures. Reservoir-scale geometries and heterogeneities of geological bodies and faults and fractures affect permeability, which are governed by microstructural processes such as creep and cementation. We present case studies that combine results from subsurface exploration, from reservoir to microscale, which may enhance subsurface utilization and reduce risks.

# Deciphering polymetamorphism in greenschist- and amphibolite-facies rocks using thermodynamic modeling and in situ U-Pb dating (Austroalpine Unit, Eastern Alps, Austria)

Marianne Sophie Hollinetz[a], Benjamin Huet[b], David A. Schneider[c], Christopher R.M. McFarlane[d], Bernhard Grasemann[a]

[a]University of Vienna, Austria, [b]Geologische Bundesanstalt, Vienna, Austria, [c]University of Ottawa, Canada, [d]University of New Brunswick, Canada

In metamorphic units where thermobarometric and geochronologic data are ambiguous or entirely lacking, the temporal interpretation of metamorphism and the identification of complex polymetamorphic histories is hampered. We present new P-T-t-D data from samples collected in two Austroalpine nappes exposed in the Eastern Alps, Austria: the structurally upper greenschist-facies Schöckel Nappe ("Graz Paleozoic," Drauzug-Gurktal Nappe System) and the structurally lower amphibolite-facies Waxenegg Nappe (Koralpe-Wölz Nappe System). Although polymetamorphism was previously inferred in the Waxenegg Nappe, the timing of metamorphism is poorly resolved and only limited geochronology exists in the Schöckel Nappe.

In phyllites and micaschists of the Schöckel Nappe, phase relations of chloritoid, ilmenite and rutile and results from thermodynamic modeling allow the reconstruction of the main metamorphic event at $\sim 470$ °C and 3-4 kbar. In situ LA-ICPMS U-(Th)-Pb dating of allanite that grew together with the peak assemblage yields and age of c. 260 Ma (Permian event). Published white mica geochronological data suggests that this unit was overprinted at c. 350-400 °C in the Cretaceous (Eo-Alpine event). In the underlying Waxenegg Nappe, garnet-bearing mica schist contains large (up to 500 $\mu$m) monazite exhibiting distinct core-rim chemical zoning. LA-ICPMS U-(Th)-Pb dating targeting the monazite cores indicate growth at c. 270 Ma during the Permian event whereas the monazite rim grew during the Eo-Alpine event at c. 90 Ma. P-T conditions for both events are reconstructed using thermodynamic modeling and careful documentation of microstructural phase relations. Pseudomorphs after staurolite and relics of plagioclase and sillimanite indicate $\sim 560$ °C and 4 kbar during the Permian event; garnet and chloritoid formed during the pressure dominated Eo-Alpine overprint at $\sim 540$ °C and 8-10 kbar.

We provide unequivocal evidence for Permian metamorphism in the Schöckel Nappe, which was hitherto unknown in this part of the Austroalpine Unit. Our results demonstrate that the metamorphic overprint during the Eo-Alpine in this unit is significantly lower grade than previously proposed. Combined with the data from the Waxenegg Nappe, there is an obvious marked increase in the Eo-Alpine peak conditions of $\sim 130$ °C and 5 kbar across the nappe contact with higher grade in the footwall compared to the hanging wall. This is in line with the existence of a major normal fault between the Drauzug-Gurktal Nappe System and the Koralpe-Wölz Nappe System in the easternmost part of the Austroalpine Unit, which is comparable to similar structures in its central and western parts. Modern thermobarometric analytical approaches coupled with high spatial resolution geochronology on accessory minerals is allowing a more thorough assessment of the subtle metamorphic histories recorded in the fundamentally important low-grade units of orogens.

## A three-dimensional mineral dendrite forest in clinoptilolite (zeolite)

Zhaoliang Hou[a], Cornelius Tschegg, Piotr Szymczak, A. Hugh N. Rice, Lutz Nasdala, Florian Fusseis, Bernhard Grasemann[a]

[a]University of Vienna, Austria

Since the "six-cornered" shape of snowflakes was first studied by Kepler in the 16th century, natural patterns have been an important scientific topic to understand the physical laws of nature. A tree-like pattern formed by mineral dendrites most widely known as a planar structure on fractures and bedding planes, record the fluid-rock interactions. Here we studied the rare natural three-dimensional mineral dendrites found in clinoptilolite (zeolite), significantly advancing our understanding of mineral dendrites growth. The mineral dendrites form a $< 15$ mm high rock-hosted fractal dendrite "forest", with trunks and branches, both having a core-rim structure, and, in the upper part of the forest, an alternating concentric core-rim layering. Fracture-derived manganese-rich fluids infiltrated the rock, forming dendrites by manganese oxide sorption into the clinoptilolite crystal lattice and infilling rock porosity, changing the rock-microstructure and composition. Dendrite complex architectures suggest that growth of the dendrite forest was a self-organization processes, with formation by particle attachment, spontaneously depleting heavy metal concentration in the infiltrating fluids. Our research demonstrates that formation of the dendrite forest was an active natural response of the rocks to the introduction of heavy metal-contaminated fluids, an effectively rock self-purification process. Our study will strongly benefit research into (synthetic) rock materials for a range of applications, including remediating water and soil pollution and nuclear waste processing, as well as in pharmaceutical uses for animal and human health.

# Late Oligocene to Early Pliocene exhumation processes and structural development in the Western Himalaya, Northern Pakistan: implications for the Cenozoic metamorphic overprint

Irum Irum, Humaad Ghani[a], Edward R. Sobel, Gerold Zeilinger, Uwe Altenberger
[a]Georg-August-Universität Göttingen, Germany

Fold and thrust belts can show changes in the sequence of structural deformation through time and as such are widely studied in the Himalaya. We present new Middle Miocene to Pliocene apatite fission track cooling ages combined with published data; these constrain temporally linked hinterland to foreland deformational and exhumation processes active in the Western Himalaya, Hazara region. The cooling ages can help to constrain when metamorphic rock were exposed in this area. The proposed model of structural evolution links the pre-deformation geometry of the leading edge of India with the impacts of Cenozoic metamorphism. The model suggests a simple framework that explains how temporally different metamorphic grade rocks coexist such that Paleoproterozoic rocks show no impacts of Cenozoic metamorphism, Neoproterozoic to Lower Paleozoic rocks retain signatures of the Ordovician metamorphism and Upper Paleozoic to Mesozoic rocks were subjected to elevated temperature-pressure conditions during Cenozoic metamorphism prior to exhumation. The results suggest that the Main Central thrust was active from Oligocene to Late Miocene and the Main Boundary Thrust was active from Middle Miocene to Late Miocene toward the foreland in the Hazara area. In the Early Pliocene, deformation shifted back to the hinterland, resulting in the development of a N-S trending anticline that created an erosional half window into the Main Mantle thrust and divided the Main Central thrust sheet into the Hazara and Swat segments. The model suggest that the present day hinterland deformation is accommodated by left lateral movement along the Balakot Jhelum fault, which is evident by abundant seismicity around the Hazara-Kashmir syntaxis area.

# Prism c slip in quartzite at greenschist facies conditions? An effect of strain compatibility in deforming quartz-white mica mixture

Petr Jeřábek

Charles University, Prague, Czech Republic

Deformed quartzite with dispersed white mica experienced intense deformation at temperatures decreasing from $\sim 600 - 400$ °C during development of the Branná detachment zone in the NE part of the Bohemian Massif. The studied quartzite locally contains nearly monomineralic quartz bands with relics of highly lobate and coarser-grained ($\sim 300$ $\mu$m) microstructure M1q overprinted by finer-grained ($\sim 175$ $\mu$m) microstructure M2q. The mixed quartz and white mica domains show further decrease in quartz grain size to $\sim 125$ $\mu$m and $\sim 90$ $\mu$m in the dispersed white mica M2qm microstructure and the interconnected white mica M3qm microstructure, respectively. The M1q microstructure is associated with higher temperatures of $\sim 600$ °C of the earlier deformation while the M2q-M3qm microstructures are associated with $\sim 400$ °C of the overprinting deformation.

The texture of the earliest M1q microstructure is difficult to decipher due to strong overprint by M2q, however crystallographic orientation of M1q grains is similar to the overprinting M2q. Large M1q grains show subgrains compatible with grain size reduction by dynamic recrystallization to M2q microstructure. Crystallographic Preferred Orientation (CPO) in M2q domains shows broad single to crossed girdle pattern of c-axes. In contrast, domains with the white mica-bearing M2qm and M3qm microstructures show pronounced scatter of c-axes away from the single girdle distribution towards the orientation of c-axes subparallel to lineation. This change in texture from the M2q to M3qm is also accompanied by the decreasing texture j-index. It is interesting to note that the M2qm-M3qm grains with their c-axes subparallel to lineation are in most cases in contact with white mica. In addition, white mica shows pronounced crystallographic orientation relation to quartz manifested by the basal (001) planes of white mica being coplanar to positive rhomb planes $\{10\bar{1}1\}$ and basal planes (0001) of quartz. Misorientation analysis of subgrain boundaries in quartz suggested preference of prismatic $\{m\}\langle a\rangle$, and rhombic $\{z\}\langle a\rangle$, $\{\pi'\}\langle a\rangle$ slip systems for the development of M2q microstructure and prismatic $\{m\}\langle a\rangle$, $m\langle a+c\rangle$ and $m\langle c\rangle$ slip systems for M3qm. Comparison of the inverse pole figures for M2q and M2qm-M3qm microstructures suggests CPO scattering in relation to activity of prismatic [c] slip. However, the temperature estimates of $\sim 400$ °C related to the development of M2q-M3qm microstructure appear to be too low for activation of prismatic [c] slip system. As such, the development of basal subgrain boundaries might be explained by deformation partitioning between the weak white mica and stronger quartz evoking behavior similar to the Rachinger creep, i.e. grain boundary sliding accompanied with simultaneous intracrystalline plasticity. This deformation mechanism could lead to strain compatibility issues in deforming quartz-white mica mixture and consequently to activation of the unexpected prismatic c slip.

# Litho-tectonic control on the Quaternary landscape of the western Sub-Himalaya, India: Quantitative analyses of the landscape

Neha Joshi[a], Mjahid Zebari, Christoph Gruetzner[a], Kamil Ustaszewski[a]
[a]Friedrich-Schiller-Universität Jena, Germany

Following the onset of continent-continent collision of the Indian and Eurasian plates, the interplay between endogenic and exogenic processes has shaped the landscape of the Himalayas. The Himalayan orogen hosts various litho-tectonic entities that are mainly parallel to the orogen (from Tethys Himalaya to sub-Himalayan sequence). Its shape is also influenced by along-strike variations in the geometry and the kinematics of major morphotectonic units (from Kashmir to Assam). In this study, we focus on the active southernmost fold and thrust belt, the Sub-Himalaya (SH). The SH extends for $\sim$ 450 km between Kashmir and Garhwal and comprises mainly Tertiary units. We analyze the spatial variability of morphometric parameters such as slope, relief, surface roughness, and hypsometric integral using SRTM 1 (30 m) digital elevation models. In our analyses we also included data on the subsurface geometry of folds and faults, their deformation rates, and data on rock erodibility. The spatial distribution of the geomorphic parameters correlates with the relative rock uplift rates, where higher values were found in those areas that are characterized by recent tectonic activity. The distribution of slope and surface roughness regionally highlights the effects of differential rock erodibility independent of deformation rates. The surface roughness also varies with elevation and the extent of river incision, owing to changes in the base level within the same lithology. The variation of relief within SH is controlled by the significant erosion of relatively young deformed structures owing to high rock erodibility (0.1 mm $yr^{-1}$ $Pa^{-1}$). The hypsometric integral was found to show high values along the regions corresponding to higher rock uplift rates and recent tectonic deformation, independent of rock erodibility. Our results emphasize the importance to distinguish the contributions of relatively young tectonic movements and rock erodibility on landscape evolution of the western SH.

# Tectonic and morphometric analyses of circum-Tharsis wrinkle ridges system on Mars

Oguzcan Karagoz[a], Thomas Kenkmann[a], Gerwin Wulf
[a]Albert-Ludwigs-Universität Freiburg, Germany

Wrinkle ridges are prominent tectonic landforms on terrestrial planets including the moon and developed under compressional stress. They are linear to sinuous positive relief landforms, tens to hundreds of kilometers long, sometimes discontinuous, bifurcating, or forming en echelon arrays [1]–[2]. We investigated the system of wrinkle ridges that concentrically surrounds the ∼ 3500 km diameter Tharsis dome on Mars. Our study area is Lunar Planum, situated east of the Tharsis Rise. We used methods to construct balanced cross-sections of fold-and-thrust belts [3] that are based on conservation of area and volume to determine the nature of deformation and to quantify the amount of shortening and the depth of detachment faulting. We used the remote sensing data of the high-resolution Context Camera (CTX) (∼ 6 m/px) [4] and the High Resolution Imaging Science Experiment (HiRISE) (∼ 0.25 m/px) [5]. The morphometric analyses indicate that height and width of wrinkle ridges at Lunae Planum systematically decrease with increasing distance from the center of the Tharsis rise from west to east. The results show that horizontal shortening decreases from 4.75 % to 1.25 %, or ∼ 116 m to ∼ 56 m from west to east. Sections through wrinkle ridges provided by an escarpment at Kasei Valles and by steep walls of impact craters expose thrust faults beneath the wrinkle ridges that dip at $38^\circ \pm 5^\circ$, on average. Based on [3], we developed a model of fault-propagation folding [6] for wrinkle ridges and show that the observed thrust faults form along the frontal fold axial planes of the anticlines. At depth, these faults merge into more gentle thrust ramps of $20^\circ \pm 5^\circ$ dip. That is connected to a sub-horizontal detachment, which rises from ∼ 4 km in the west to ∼ 2.6 km in the east, measured from the surface. The very gentle eastward dipping topographic slope of Lunae Planum and the eastward rising detachment define a narrow wedge that is interpreted as an incipient critical taper with a tectonic push induced by the Tharsis rise. Here, we suggest that the mechanically weak detachment is likely localized in a water-bearing crustal layer underneath a thick permafrost table. Fluid overpressure conditions may enable yielding and slip on the detachment. Hydrous mineral reactions on the slip planes and flood basalt layers that gently dip to the Tharsis center due to flexural loading may additionally weaken the basaltic rocks and contribute to detachment faulting.

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# Thrusting and subduction on Venus: tectonic processes in Aphrodite Terra

Thomas Kenkmann[a], Antonia Veitengruber, Gerwin Wulf
[a]Albert-Ludwigs-Universität Freiburg, Germany

Venus and Earth are similar in size, density, and composition but tectonic plates seem to lack on Venus. Here we investigate deep troughs, so called Chasmata, in the central part of Aphrodite Terra. This is a topographically elevated region on Venus that expands along the equator with a length of $\sim$ 14000 km. The nature of this large-scale uplift is controversial and includes contrasting hypotheses of a “continent” formed from lighter rock, the uplift due to thermal buoyancy of mantle material, or mantle downwelling that causes the surface crust to compress and thicken.

The formation of Chasmata is crucial for the understanding of Aphrodite Terra and Venus tectonics in general. Some of the Chasmata strike ENE-WSW to E-W, while others surround large circular Corona structures. Coronae are roughly circular ring features with a fractured ridge annulus that are manifestations of small-scale mantle upwellings driven by thermal buoyancy [1]. Chasmata that surround these Coronae have been interpreted as trenches formed by plume-induced subduction [2]. Alternatively, they have been considered as extensional rifts that emanate from the volcanic center at Atla Regio east of Aphrodite Terra [3]. Still others suggested that neither divergent nor convergent tectonics occur at the Chasmata but vertical adjustments dominate [4].

We will present the deformation imprint of several Chasmata and analyze 20 topographic and Bouguer gravity profiles through the troughs based on the Magellan SAR global mosaics, the Magellan global topography and related Bouguer anomalies. Most troughs show asymmetric profiles. The steeper slopes merge into a strongly elevated ridges that trend parallel to the troughs while the gently dipping slopes merge into broader rises of lesser height. In case of concentric Chasmata, the steep slope is always the inner slope and the gentle slope merges into an outer rise. The mean depth of the trenches is 1568$\pm$957 m, based on a local reference level, the elevation difference between trough and inner ridge is 3368$\pm$1717 m, and the elevation differences between the inner ridge and the outer rise is 1283$\pm$1043 m. Gravity profiles show a local positive excursion at the outer rise and a negative anomaly at the inner ridge. Radar imagery show significant backscatter signals at the base of the steep slopes indicating the exposure of localized thrust planes and corresponding rough surfaces formed by fault breccia of a subduction channel. Our data indicate that thrust faulting and subduction play an important role for Chasma formation. Steep slopes with inner ridges are formed by the hanging wall, while the gentle slope and outer rise represents bending of the footwall [2]. We calculated a mean elastic plate thickness of 55$\pm$27 km based on 20 cross sections. Despite there is no apparent mosaic of moving plates on Venus, there is evidence for plume-induced subduction [2] and this also seems to operate in straight Chasmata.

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# Tesserae terrains on Venus: key for understanding the mechanism of resurfacing

Thomas Kenkmann[a], Aline Müller, Gerwin Wulf
[a]Albert-Ludwigs-Universität Freiburg, Germany

Venus is believed to represent a one-plate planet with "stagnant lid" convection. Despite the high surface temperature of 460°C, the roughly 30 km thick crust has a high strength due to the absence of water. According to the rather uniform impact crater density, Venus´ surface formed in a relatively short period of time not more than 500 Myr ago. To explain this, it is assumed that a major resurfacing event must have taken place.

To understand the tectonic history of Venus and the mechanism of resurfacing we have studied one of the Tessera regions using Magellan radar imagery. Tesserae show intense brittle and ductile deformation with intersecting faults. Tesserae are elevated regions that are believed to be slightly older than the rest of Venus [1,2]. The rough surfaces of Tesserae with close-spaced fault networks have a high radar backscatter. For our structural analysis we inverted the backscatter radar imagery. We investigated the northern part of Manatum Tessera (4.7°N/65°E) in an area of about 700x500 km. Rocks show a foliation with compositional banding expressed by slight differences in the radar backscatter intensity. The foliation mostly strikes WNW-ESE and dips steeply, with local unconformities and strata bending present. Locally high strain zones are indicated by more intense foliation. Fold orientations follow foliation strike and have a preferred south vergence and wavelengths of 6-8 km. The rough surface of the Tessera is a result of layering, the presence of folds, and in particular the deep incision of normal faults and fractures. In the study area, N-S trending faults that border simple graben structures intersect NE-SW and NW-SE striking normal faults. These have locally a trans-tensional character. Fault intersection governs the local relief, which is segmented into lensoid highs. Grabens have down faulted interiors that are often covered with smooth basaltic lava. The graben fills are interconnected with other Inter-Tesserae plains.

Strata tilting along with folding due to N-S compression and the formation of high strain ductile shear zones are the oldest geological features. NE-SW and NW-SE transtensive normal faulting occured next and was followed by the formation of graben structures. Lava coverage in Inter-Tessera plains is the youngest event.

Tesserae are key for understanding the tectonic history of Venus. Folding and ductile deformation of Tesserae imply a relatively weak and thin lithosphere and a high geotherm at that time. Subsequent brittle normal faulting indicates a strength increase and decrease in geothermal gradient. When smooth lava plains buried parts of the Tesserae regions, deformation has been of subordinate importance. The morphotectonic inventory is consistent with a predicted increase in lithospheric thickness with time and is potentially related to a transition from a mobile lithosphere to stagnant-lid convection [3]. We postulate here that the early deformation recorded in the Tesserae formed during the final phase of resurfacing. Resurfacing might be enabled by large-scale rock tilting.

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# Exhumation of the Cretaceous Saualpe, Koralpe and Pohorje high pressure units of the Eastern Alps – preliminary results

Ruth Keppler[a], Nikolaus Froitzheim[a], Michael Stipp[b]
[a]University of Bonn, Germany, [b]Martin-Luther-Universität Halle-Wittenberg, Germany

The Saualpe-Koralpe high pressure (HP) complex as well as the HP units of the Pohorje mountains are part of the Eoalpine HP belt, which extends over about 350 km from west to east. It formed in conjunction with the Cretaceous orogenic cycle in the Eastern Alps and comprises eclogite lenses in a matrix of gneisses and micaschists. The precursors of the eclogites are partly pre-Variscan mafic plutonic and volcanic rocks, partly gabbro intrusions in a Permian rift within the Austroalpine continental crust. Parts of the Austroalpine continental crust including the Permian rift were subducted southeastward during the Cretaceous. This led to eclogite facies conditions at 100-90 Ma. The Saualpe, Koralpe and Pohorje units reached peak pressure conditions of 2.2-2.4 GPa/630-690 ˚C, 1.8-1.9 GPa/670 ˚C and 3.0–3.7 GPa/710–940 ˚C, respectively. PT-analyses, microstructural investigations and dating predict different contrasting models for the exhumation of these units. Among these models are a Chemenda-type wedge extrusion, slab extraction as well as the exhumation through a low angle extensional fault.

Within our study we intend to unravel the deformational history of the Koralpe, Saualpe and Pohorje HP units during their exhumation. In a first step samples were taken in the Koralpe Complex in a 1 km long profile north of the Schirchleralm near Deutschlandsberg, Austria. The set includes two pristine eclogites, one of these fine grained and one coarse grained, a retrogressed eclogite as well as a gneiss sample. Crystallographic preferred orientation (CPO) analysis was performed with electron backscatter diffraction (EBSD) at the transmission electron microscope of the Institute of Geosciences at the University of Cologne.

In the fine grained eclogite the ⟨001⟩ axis of omphacite shows an alignment in lineation direction while ⟨010⟩ is distributed within a girdle normal to the lineation with a maximum normal to the foliation plane. This indicates constrictional deformation. In the coarse grained eclogite the ⟨001⟩ axes show more of a girdle distribution with several maxima within the foliation plane, which could point to flattening strain. In the retrogressed eclogite the hornblende ⟨001⟩ axes exhibit a maximum in lineation direction with some distribution within the foliation plane, while the ⟨100⟩ axes show a maximum normal to the foliation plane. This indicates flattening to plane strain. In the retrogressed eclogite sample plagioclase also shows a pronounced CPO. The gneiss shows a pronounced foliation and stretching lineation indicative of dominant plane strain conditions. Quartz {0001} axes in the gneiss sample show a maximum at an angle to the foliation normal indicating a top-to-the-north-east sense of shear. While the sample set is still too small to make large scale tectonic interpretations for the exhumation of the Koralpe Complex, they show a very variable and complicated deformation history of the rocks involved.

# Evolution of the modal phase composition in a high-grade shear zone, S-Sweden

Meggy Jessica Kerzig, Rüdiger Kilian, Michael Stipp, Rebecca Kühn
Martin-Luther-Universität Halle-Wittenberg, Germany

Polymineralic rocks constitute the major proportion of the lithosphere. In these rocks, dissolution-precipitation creep (DPC) may be considered as an important deformation mechanism, especially at high grade metamorphic conditions (e. g. Wintsch & Yi, 2002). DPC involves material transport. Phase proportions of a stable assemblage are subject to change with varying metamorphic conditions. In order to test the influence of DPC on bulk and modal phase composition, we analyze samples from an amphibolite facies shear zone in the Stora Le-Marstrand Formation (Sveconorwegian orogen, southern Sweden).

In the approximately 15 m wide shear zone, a pre-existing foliation and lineation progressively rotate into parallelism with a new mylonitic foliation and stretching lineation in the center of the shear zone. In order to track the transformation of fabric elements, the foliation and lineation are expressed as an orientation (in the mathematical sense). The angle of the net rotation ($\alpha_n$ ) is defined as the angle between each orientation and a reference orientation taken from the center of the shear zone. Composition of samples collected across the strain gradient was analyzed using large-area, $\mu$XRF-derived element maps. From those, phase maps as well as bulk composition were derived.

The metasediments are composed of quartz, plagioclase, potassium feldspar, biotite and white mica defining a coarse compositional layering outside the shear zone. Layers of a homogeneous phase mixture appear towards the center of the shear zone. While quartz aggregates show microstructures compatible with dislocation creep at high temperature (low stress) conditions, indications for DPC include the truncation of zoned feldspars or mica precipitation.

The result of the modal phase analysis indicates that the fraction of potassium feldspar decreases from 25% at the rim to $< 10\%$ in the center of the shear zone while the fraction of plagioclase shows the opposite trend and increases from 10% to $\sim 22\%$. For both, the changes in modal volumes correlate well with $\alpha_n$. Modal proportions of quartz, white mica and biotite do not show any clear relation with respect to the deformation gradient. The change in modal composition is accompanied by a decrease in total potassium and an increase in sodium towards the shear zone center.

Our results indicate that the shear zone can be considered being an open system at the scale of several meters. We suggest that DPC is an efficient mechanism to adjust the phase assemblage to new tectono-metamorphic conditions.

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## Using crystal dispersion axes to reveal strain partitioning in experimentally deformed quarzites

Rüdiger Kilian, Michael Stipp
Martin-Luther-Universität Halle-Wittenberg, Germany

Deformation by a dislocation mechanism is known to result in a variable intragranular lattice orientation. From the orientations present within a deformed grain, an axis can be computed around which crystal directions are dispersed, representing the rotation axis of a bend crystal. This axis has also been termed crystal vorticity axis, used in naturally deformed rocks to infer the bulk kinematics of flow (Michels et al., 2015). To investigate the relation between crystallographic preferred orientation (CPO) and strain we analyzed EBSD data of quartzites experimentally deformed in axial shortening (Stipp & Tullis, 2003) and general shear (Heilbronner & Tullis, 2006) in a Griggs type deformation apparatus. We find that in general shear experiments with a high fraction of dynamically recrystallized grains ($> 90\%$), prophyroclasts and recrystallized grains share a common distribution of crystal dispersion axes, a point maximum parallel to the expected vorticity axis of the experiment. This distribution is independent on the type of CPO developed in the different samples. Hence, we assume that the analysis of crystal dispersion axes allows to distinguish deformation features that correspond to the bulk flow from those which deviate from the overall deformation pattern.

In the axial shortening samples, strain and the fraction of recrystallized grains are generally lower (15 to 30% in the high stress experiments and up to 60% in the low stress experiments). Apart from a Dauphiné-induced ordering of poles to {10-11} and {01-11}, no overall significant CPO developed. Crystal dispersion axes of large quartz grains form a girdle normal to the shortening direction which corresponds to the global kinematic reference frame. However, overall crystal dispersion axes of the fraction of small, recrystallized grains have a weaker ordering and form variable and broad point maxima which are not easily related to the global kinematics. Individual patterns are interpreted to relate to the local kinematics between large porphyroclasts.

The results obtained from the axial shortening experiments imply that the porphyroclasts constitute a load bearing framework and aggregates of small, recrystallized grains can be assumed to deform at a similar rate but within a local kinematic reference frame. The externally measured load relates to the load bearing framework. Assuming that fine-grained aggregates of recrystallized grains are usually interpreted to possess a lower viscosity than porphyroclasts, the aggregates of recrystallized grains in the analyzed experiments should deform at a lower differential stresses than the load bearing framework. The implications for the recrystallized grain size piezometer are that stresses related to a given grain size represent an upper bound.

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# Subduction, accretion and exhumation processes in the Internal Western Alps (Switzerland, Italy) - Insights from LA-ICP-MS U-Pb dating of garnet

Frederik Kirst[a], Aratz Beranoaguirre, Leo J. Millonig, Richard Albert, Axel Gerdes, Jolien Linckens[a]

[a]Goethe University Frankfurt am Main, Germany

The evolution of Alpine-type orogens is characterized by accretion of continental and oceanic units to the upper plate due to progressive subduction of oceanic basins and continental blocks. Detailed multi-disciplinary studies are necessary to decipher the tectonometamorphic history of tectonic units in such accretionary orogens. The key question that often remains is, however, to what extent tectonic units are composed of smaller crustal or lithospheric slivers that assembled during subduction, accretion and exhumation. The Internal Western Alps of Switzerland and Italy represent a stack of tectonic units derived from the Adriatic continental margin and Piemont-Ligurian oceanic lithosphere. These units were metamorphosed during Upper Cretaceous to Paleogene SE-directed subduction underneath the Adriatic continental margin. We analyzed 13 high- to ultrahigh-pressure (HP to UHP) metasediment and eclogite samples from 3 different localities along the boundary zones between the continental Dent Blanche nappe in the hanging wall, the underlying composite Combin zone, and the ophiolitic Zermatt-Saas zone in the footwall. These boundary zones represent major structural and metamorphic discontinuities within the orogenic wedge and probably represent fossil subduction and/or exhumation interfaces. We used LA-ICP-MS U-Pb dating of garnet to determine the geochronological architecture of the investigated subunits and the degree of tectonic mixing.

Two localities, near the Oberrothorn in the Zermatt area and at Lago di Cignana in the western Valtournenche of Italy, are located in the immediate footwall of the Combin zone whereas the third locality, Becca d'Aver in the western Valtournenche, is located at its top. A garnet calcschist from the Oberrothorn locality yielded an age of ca. 50 Ma. Garnet ages for 7 metasediment and eclogite samples from the UHP unit at Lago di Cignana yield an age range between ca. 65 and 47 Ma. 6 mainly quartz-rich metasediments from Becca d'Aver gave U-Pb ages of $\sim 51 - 46$ Ma, apart from one sample which yielded an age of ca. 63 Ma. All the acquired ages can be attributed to metamorphism on the prograde path according to the distribution of major bivalent cations in garnet. From our results we draw the following conclusions:

- The large range of prograde garnet ages suggests prolonged subduction of continental margin and oceanic units between ca. 70 and 45 Ma with accretion of only small crustal/lithospheric fragments to the upper plate.
- The spread of ages within subunits previously considered coherent, like the UHP unit at Lago di Cignana, suggests a large degree of tectonic mixing along a long-lived subduction interface or narrow subduction channel, respectively.
- The overlap of garnet ages for samples in the footwall and at the top of the Combin zone suggests that they experienced prograde metamorphism along the same subduction interface and were only later separated during exhumation.

Our study stresses the value of LA-ICP-MS U-Pb garnet dating to constrain tectonic processes. It also highlights the importance of detailed geochronological investigations to unravel the internal structure of tectonic units and to constrain their formation, assembly or even disassembly during subduction, accretion and exhumation.

## Fluid-rock interactions along the subduction interface - The record within (ultra)high-pressure metasediments (Western Alps, Italy)

Frederik Kirst, Jolien Linckens

Goethe University Frankfurt am Main, Germany

In the Internal Western Alps of Switzerland and Italy, a stack of ocean- and continent-derived tectonic units, metamorphosed during Upper Cretaceous to Paleogene SE-directed subduction underneath the Adriatic continental margin, is exposed. The boundary zones between these units often represent fossil subduction interfaces and are frequently marked by metasedimentary sequences. We investigate mainly quartz-rich metasediment samples from two high- to ultrahigh-pressure ((U)HP) units in the western Valtournenche of Italy, the Becca d'Aver sliver and the UHP Lago di Cignana unit. All samples display thin bifurcations of garnet around quartz and occasionally calcite grains ('honeycomb garnet'). The aim of our study is to constrain their mechanical and metamorphic significance and to unravel the processes leading to their formation.

Classical honeycomb-type inclusion patterns with straight edges between adjacent quartz inclusions only appear in the blueschist-facies samples. In the UHP sample, quartz inclusions are rather rounded and larger inclusions have an amoeboid shape. Electron backscattered diffraction (EBSD) reveals that quartz inclusions in the HP samples as well as smaller inclusions in the UHP sample do not show a crystallographic preferred orientation (CPO). The lack of a CPO shows that quartz grains were not deformed by dislocation creep prior to garnet formation or only formed when garnet crystallised. Backscattered electron imaging confirms that garnet preferentially occurs along quartz grain boundaries. In some cases, several amoeboid-shaped quartz inclusions in the UHP sample belong to one grain (misorientations $< 10°$), indicating dissolution of these quartz grains. In addition, garnet-quartz boundaries are often irregular and show bulging phase boundaries, indicating that diffusion occurred between quartz and garnet. Calcite inclusions show subgrains and sometimes have similar orientations ($< 10°$) with straight garnet-calcite boundaries, suggesting fracturing of pre-existing deformed grains. Garnet grains are usually xenomorphic in all samples and often have a tabular and elongated shape. Garnet often displays a typical compositional zonation of major bivalent cations but also shows irregular chemical zonation patterns and compositional perturbations in subdomains. The occurrence and orientation of quartz inclusions often traces the compositional zonation. Garnet is usually crystallographically homogeneous but also shows slight misorientations which then often correlate with inclusional or compositional domains.

Our observations suggest a strong link between the migration of fluids, opening of grain-scale fluid pathways and fluid-mediated garnet growth. Based on microstructural, textural and petrological analyses we propose a model that involves

- release and migration of fluids from the downgoing plate into overlying metasediments along the subduction interface
- dynamic wetting of quartz along grain boundaries and in part fractured calcite grains due to high pore fluid pressures
- precipitation of garnet from the fluid phase
- dissolution and reprecipitation of quartz during fluid-mediated metamorphism, especially towards UHP conditions

These coupled deformation-fluid-metamorphism processes may affect (quartz-rich) metasediments along a large portion of the subduction interface, from blueschist-facies to UHP conditions and may therefore have a significant impact on interplate rheology and coupling/decoupling.

# How to form an intracontinental Benioff zone: the Pamir slab

Jonas Kley[a], Edward R. Sobel, Thomas Voigt, Johannes Rembe
[a]Georg-August-Universität Göttingen, Germany

The western and northern sectors of the northward convex Pamir arc are underlain by a Benioff zone dipping steeply east to south, traced by earthquakes to depths of 250 km in the SW and 150 km in the NE. This slab has been interpreted early on to result from intracontinental subduction (Burtman & Molnar 1993) due to the northward advancing Pamir overriding and pushing down the foreland lithosphere by a distance equivalent to the slab length. Seismological evidence now shows that the slab does not comprise felsic continental crust, while recent paleogeographic evidence for a pre-Cenozoic arc shape of the Pamir limits the magnitude of its northward convergence to markedly less than the slab length. The Pamir is surrounded in the west and north by thin-skinned foreland fold-and-thrust belts of the Tajik Basin and Alai Valley. Foreland shortening decreases northeastward from a maximum of 150 km in the Tajik belt to 75 and 30 km in the Alai Valley and westernmost Tarim Basin. This trend approximately matches that of slab length but is again insufficient to explain its downdip extent. These problems do not affect models that interpret the slab as delaminating and sinking mantle lithosphere, making the slab length independent of crustal shortening. A new variant is the forced delamination scenario in which Indian mantle lithosphere indenting at depth has forced down the slab consisting of Asian lower crust and mantle lithosphere (Kufner et al. 2016). The location of the slab beneath the foreland thrust belts instead of the hinterland also suggests some amount of slab delamination and rollback towards the foreland.

Other problems of Pamir orogeny and slab formation are not solved by delamination. Existing Pamir models generally assume predominantly N-S convergence, but the shortening direction in the Tajik Basin is WNW. Its strong deviation from the convergence direction has been attributed to gravitational collapse and lateral spreading of thickened Pamir crust (Schurr et al. 2014). However, on the Pamir plateau there is no evidence for the $> 100$ km E-W extension required by such a model. Extension on the $< 8$ Ma Kongur Shan detachment of the eastern Pamir is about 35 km (Robinson et al. 2004). The WNW-verging Tajik thrust belt and long E-dipping western part of the slab thus suggest a substantial westward component of Pamir convergence.

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# A remarkable ultramylonitic shear zone in the Sveconorwegian orogen, southern Sweden

Dustin Klimpke, Rüdiger Kilian, Thomas-Johannes Degen
Martin-Luther-Universität Halle-Wittenberg, Germany

Shear zones commonly develop at rheological heterogeneities such as lithological contacts. Here we present an analysis of a small scale, ultramylonitic shear zone situated inside a metagranodiorite lens embedded in mylonitic metasediments (Stora Le-Marstrand Formation; Åseby, southern Sweden). The shear zone runs for 20 meters parallel, close (30 - 45 cm) to the lithological contact between metagranodiorite and metasediment Contrary to what could be expected from the coupling and positive feedback of strain localization and grain size, the shear zone appears to be developed in the coarse grained metagranodiorite instead along the contact or inside the fine-grained metasediment. In order to better understand this apparent contradiction, both fabrics and phase distribution in the wallrock, the shear zone and the metasediment were analyzed and compared.

The 10 - 15 cm wide shear zone is aligned parallel to the NE-dipping main foliation. The shear sense is top to NE with a NE-plunging stretching lineation. The metagranodiorite adjacent to the shear zone shows a SC'-fabric and shearband boudins. The fine grained shear zone is characterized by a SC-fabric. On the microscale, quartz shows grain boundary migration recrystallization microstructures with deformation bands and occasional chessboard extinction, which indicates deformation in the upper amphibolite facies. Nevertheless, the microstructural record also documents a partial retrograde overprint.

Microstructural analysis was based on µXRF (Bruker M4 Tornado) element maps, from which phase maps were constructed using multi-element clustering (k-means). Anisotropy of phase aggregates was quantified using the autocorrelation function (ACF). Overall deformation intensity was approximated using eigenvalue-based measures for the scattering of stretching lineations at outcrop sites.

The metagranodiorite, the ultramylonite and the metasediment consist of quartz, plagioclase, white mica, biotite and apatite. Inside the shear zone an anti-clustered phase distribution of quartz and plagioclase and isometric grain shapes indicate diffusion creep (s. l.). The phase distribution varies gradually from edge to center of the shear zone. The biotite content increases and white mica, potassium feldspar and opaque phases decrease to the center of the shear zone. In general, the modal phase compositions of the ultramylonite are more similar to the metasediment than to the metagranodiorite. The metasediment has an estimated grain size of ca. 300 $\mu$m and for the ultramylonite has a grain size of ca. 200 $\mu$m.

We interpret that the protolith of the shear zone is the metasediment sliver inside the surrounding metagranodiorite, instead of the metagranodiorite itself. Development of the ultramylonitic shear zone was most likely facilitated due to the smaller grain size of the protolith as well as the geometric anisotropy induced by the more rigid metagranodiorite. During deformation, the grain size inside the shear zone was further reduced relative to the mylonitic metasediment; however deformation was mostly isochemical, leaving the phase proportions unaltered. While, this shear zone represents a case which could easily be misinterpreted in the field. We confirm, using phase analysis, that in the studied case, lithological heterogeneities are most likely the governing factor for strain localization.

# Exotic granite boulders in sandstone of the Carboniferous Ruhr basin, Germany

Mathias Knaak[a], Manfred Brix[b]
[a]Geologischer Dienst NRW, Germany, [b]Ruhr-Universität Bochum, Germany

The recent discovery of a larger elongate (ca. 4 x 10 cm) poorly rounded granitic boulder in a quarry near Herdecke sparked new discussions about the provenance and depositional environment of the late Carboniferous sandstones of the Ruhr basin.

The late Carboniferous Ruhr Basin has developed as peripheral foreland basins along the northern margin of the Variscan deformation front. Starting in the Lower Pennsylvanian with the Kaisberg-Formation, cyclic sequences in marine to deltaic to fluvio-lacustrine clastic sedimentary environments developed and promoted paralic coal-forming conditions. Intercalated fluvial sandstone deposited the erosional debris of the orogen approaching from the south. The Kaisberg-Formation comprises the lowermost fluvial sandstone horizons and the first paralic coal seam. These sandstones are mineralogically and texturally relatively immature, good to moderately sorted, weakly rounded, poorly bedded, medium- to coarse-grained with thin layers and nests of conglomerate comprising frequent drift wood, and have been classified as subarkose arenite due to its plagioclase and alkali feldspar content of $> 10\%$. Accordingly, rapid uplift of the source region, a low degree of chemical weathering and a high feldspar content of the source rock, and a short transport distance can be assumed for the preservation of feldspar and thus for the formation of subarkoses.

Rare single, small detrital granite pebbles/boulders have already been reported from a small number of outcrops in the beginning of last century, which, however, are no longer accessible and no more samples are available. The discovery of a larger elongate (ca. 4 x 10 cm) poorly rounded and several smaller sub-rounded and angular equigranular granitic boulders and pebbles in a quarry near Herdecke recently, sheds new light on the controversial perspective of the depositional history of these clastic sediments.

The felsic source of the subarkose arenite and the granitic boulder are thought to be related to proximal Pre-Variscan granitic/gneissic source rocks which formed the basement and margin of the basin. At present, however, no such rocks are known to occur in the vicinity of the Ruhr area, nor are they believed to have outcropped in the vicinity at the time of deposition. Furthermore, the depositional and climatic environment required for preservation of igneous/metamorphic minerals such as feldspar and mica appear to be in contradiction with contemporaneous sub-tropical semi-humid climatic conditions of coal formation.

The presented work is at an initial stage. Further research is being considered to better understand the origin of the source rock and the climatic and depositional constraints on the formation of these deposits.

# Scaled analogue experiments simulating the mechanical effect of magmatic centres subjected to transpression on the evolution of faults

Talitha Knauer, Jan Oliver Eisermann, Ulrich Riller
Universität Hamburg, Germany

An outstanding issue in magmatic arc tectonics is to elucidate the extent to which magmatic centres serve as mechanical anisotropies under overall shortening. This process may generate faults, which in turn may control ascent and eruption of magma. We examine this issue by employing scaled analogue experiments tailored to volcano-tectonic processes at the northern terminus of the Liquiñe-Ofqui fault zone (LOFZ) in the Southern Andes. Here, the western margin of the 2.6 Ma Caviahue caldera is located about 10 km to the NE of the LOFZ, one of largest known intra-arc fault zones on Earth accommodating dextral transpression. Interestingly, the NE-striking Lomín Fault connects the northern terminus of the LOFZ with the caldera margin exactly where the Late Pliocene to active Copahue composite volcano is located. Thus, it is conceivable that the Caviahue caldera forms a mechanical anisotropy, which led to the formation of the Lomín Fault as a bridge structure, in turn controlling the location of Copahue volcanoe.

To explore the development of the Lomín Fault as a bridge structure, scaled analogue experiments were conducted using the MultiBox. This modelling apparatus consists of two halves, one of which can be displaced horizontally with regard to the other, thus simulating dextral strike-slip on the LOFZ. In addition to horizontal shearing, pistons within the MultiBox impart various components of transverse shortening. Model crust consisted of viscous material (PDMS-corundum sand mixture), simulating the lower crust, and granular material (quartz sand) modelling the brittle upper crust. The topographic depression of the Caviahue caldera is modelled by placing a plastic template, resembling the shape of the caldera, onto the model lower crust prior to sieving the granular material onto the viscous material. Removal of the template prior to the onset of the experiment generates the depression. Variation of model caldera size and kinematic boundary conditions helped to identify respective variations in surface strain and kinematics, imaged via digital image correlation.

In all experiments, a bridge structure, akin to the Lomín Fault in nature, propagated from the model LOFZ toward the model caldera. Moreover, a circular zone of dilation developed close to the intersection of the bridge structure with the model caldera margin. In fact, this zone coincides with the location of Copahue volcanoe in nature. Finally, much of the model depression experienced horizontal dilation, and this agrees with the pervasive presence of dilation zones transecting the caldera floor in nature. The fact that any of these model structural characteristics are apparent, regardless of location and size of the model depression and applied kinematic boundary conditions, suggests that the Lomín Fault likely formed a bridge structure controlling the location of Copahue volcanoe.

# The displacement field of simple shear and its eigendirections: identical cause for the stress orientation on the San Andreas fault, S-C fabrics, and the sigma-delta clast systematics in mylonites

Falk H. Koenemann
Aachen, Germany

The theory of deformation was founded by Euler, Coulomb, Lagrange, Poisson, Cauchy in the late 18th/early 19th C. Elastic deformation is by nature a change of state in the sense of the First Law of thermodynamics (Helmholtz 1847); this cannot be concluded from the textbooks which are written to this day entirely in the Euler-Lagrange tradition. It is plainly impossible to understand deformation of solids without the concept of physical work and conscious consideration of bonds (discovered 1830 and 1949); there is no valid definition of the elastic potential, which is the elastic work done. The Cauchy stress tensor is mathematically refuted; the strain tensor is physically irrelevant (2008-2, 2014). The full set of concepts required for a modern understanding is available since 1870. A deformation theory founded on modern concepts has been overdue for 150 years. The conventional thermodynamic theory was written in scalars (P, V, T), implying isotropic boundary conditions. The new approach (2008-1) transforms the thermodynamic theory into vector field form (f, r, T) to handle anisotropic loading conditions. A new thermodynamic state function has been discovered, the shear dilation: it is caused by the work done by shear forces; it has the effect that any anisotropically loaded substance is constitutionally expanded, and therefore potentially in a metastable state. The shear dilation changes the understanding of the loaded state in the most profound ways.

Equilibrium in the elastically loaded state exists by definition as long as no bonds are broken. Therefore, it is possible to calculate the extending and the contracting eigendirection of the displacement field. They are not mutually perpendicular, but oriented at 11° and 112° to the bulk foliation plane. They divide the displacement field into two synthetically rotating and two antithetically rotating sectors, relative to bulk shear sense. Delta clasts are observed exclusively in the latter. The calculated contracting eigendirection correlates precisely with the observed stress direction along the San Andreas fault (112±14°), the joint orientation in mylonites, and the delta-sigma divider line. The calculated extending eigendirection at 11° to the foliation plane correlates precisely with the S-plane in S-C fabrics, and sigma-clasts in mylonites align with it. The C-plane of S-C fabric runs along the bisector of the angle enclosed by the eigendirections. The fabric properties of shear zones are therefore fully explained. Calculations for work done in elastic and plastic pure and simple shear indicate that (1) elastic simple shear costs 8% more energy than pure shear; whereas (2) plastic simple shear costs ca. 30% less energy than pure shear. These substantial differences in deformation work are supported by experimental evidence. All natural observations known to this author from elastic deformation, plastic and viscous flow fully support the new approach. It explains all the enigmatic observations in elastic, viscous and plastic deformation known to this author.

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# Tectonic evidence for a Late Devonian / Early Carboniferous North American subplate during the formation of Pangea

Uwe Kroner[a], Thorsten Nagel[b]

[a]TU Bergakademie Freiberg, Germany, [b]Aarhus Universitet, Denmark

Western Pangea originated from the late Paleozoic collision of Gondwana with Laurussia. This continent-continent collision took place over ca. 150 Ma (Devonian – Permian) and resulted in a vast diffuse plate boundary zone of the Acadian – Variscan – Alleghenian orogenic belt. Although collision mainly affected the Appalachian side of the North American Craton (Laurentia), there are additional and short lived orogenies at different edges of Laurentia in the late Devonian / early Carboniferous. The formation of the Ellesmerian fold and thrust belt of the Canadian Arctic coeval with inversion tectonics of Svalbard displays frontal convergence. In contrast, the Antler orogeny at the western edge of Laurentia was associated with sinistral transpressional tectonics. In the Caledonides of NE-Greenland, i.e., at the opposite side of the craton, the exhumation of early Carboniferous UHP complexes is accompanied by dextral intra-continental strike slip tectonics. It is important to note that these tectonics are genetically unrelated to the formation of the Greenland-Scandinavian Caledonides because this enigmatic intracontinental subduction-exhumation event is significantly younger than the formation of late-post Caledonian sedimentary basins.

Here we present a plate-tectonic model explaining these orogenies with the existence of a northward moving, late Devonian / early Carboniferous North American subplate. In the early Devonian, initial collision of a W-African promontory of Gondwana with the Midland Micro-Craton of Laurussia initiated the formation of Proto-Pangea. Plate tectonic reorganization culminated in the late Devonian opening of Paleo-Tethys and ongoing clockwise convergence of Gondwana relative to Laurussia. This plate tectonic reorganization resulted in the formation of a N-American subplate. Thus, ongoing collision at the diffuse plate boundary zone of the Appalachians is accompanied by the northward motion of a decoupled Laurentian lithosphere. The convergence of the leading edge of Laurentia with the Arctic part of Laurussia caused the Ellesmerian / Svalbardian orogeny, i.e., the formation of a frontal external fold and thrust belt north of Laurentia. In contrast, the transform boundaries of the subplate, i.e., the Panthalassan and the Greenlandian side of Laurentia are dominated by sinistral and dextral wrench tectonics, respectively. The exhumation of latest Devonian – earliest Carboniferous UHP- complexes in the Caledonides of E-Greenland is not the expression of the formation of Laurussia but displays post-Caledonian plate convergence of Gondwana relative to Laurussia.

# Deformation and CPO in low-grade serpentinites from the Atlantis Massif

Rebecca Kuehn[a], Jan H. Behrmann[b], Rüdiger Kilian[a], Michael Stipp[a], Bernd Leiss[c],

[a]Martin-Luther-Universität Halle-Wittenberg, Germany, [b]GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany, [c]Georg-August-Universität Hamburg, Germany

Physical properties of rocks are mostly controlled by the modal composition, crystallographic preferred orientation (CPO) and microstructure of a rock. One of the most significant physical properties related to the interpretation of seismic data are the elastic properties of a mineral aggregate. Changes of elastic properties - and hence changes in our interpretation of the tectonic architecture of certain regions - can be related to compositional changes, mineral reactions and deformation.

In order to explore the impact of mineral reaction and deformation on elastic anisotropy, we study oceanic serpentinites formed by hydration of peridotites at low-grade metamorphic conditions. Samples originate from the Atlantis Massif, an Oceanic Core Complex located at 30°N, Mid-Atlantic Ridge. During IODP Expedition 357, oceanic serpentinites were recovered from drill cores along the southern wall of the Massif. Completely serpentinized samples displaying variable microstructures were analyzed regarding the influence of microstructure and CPO on the overall elastic anisotropy. Microstructure analysis was based on optical microscopy and large area $\mu$XRF mapping. For CPO analysis synchrotron high energy X-ray diffraction in combination with the Rietveld texture analysis was applied and the derived CPO was used to compute seismic properties.

Serpentinites with a typical mesh microstructure are interpreted to represent undeformed samples which show a close to uniform CPO. The increased fabric anisotropy of vein-like magnetite aggregates is interpreted to be related to an increase in deformation. These samples show a single c-axis-maximum and increased CPO strength. In the deformed samples, calculated seismic anisotropies show up to $> 10\%$ anisotropy for compressional waves (Vp) and shear wave splitting up to 0.15 km/s. Hence, we suggest that such an anisotropy can be used to differentiate deformed from undeformed zones in seismic data sets using the elastic anisotropy data.

# The Sierra de Aguirre Formation, Uruguay: Post-Collisional Ediacaran Volcanism in the Southernmost Dom Feliciano Belt

Hernan Silva Lara[a], Siegfried Siegesmund[a], Klaus Wemmer[a], Mathias Hueck[a], Miguel A.S. Basei[b], Pedro Oyhantçabal[c]

[a]Georg-August-Universität Göttingen, Germany, [b]University of São Paulo, Brazil, [c]Universidad de la República, Uruguay

In Uruguay, Neoproterozoic basins related to the post-collisional stage of the Dom Feliciano Belt have been studied in different levels of detail. Several aspects like the timing of opening and filling, the geometry and the source areas, as well as the relationship with other geological processes still remain controversial. Between them, the Sierra de Aguirre Fm. preserves an important and scarcely studied record of volcanic activity related to the post-collisional magmatic activity of the belt. New stratigraphic and petrographic studies indicate that this formation is composed of pyroclastic fall and flow deposits and lavas, deposited under continental conditions, and metamorphosed under low greenschist facies conditions. Pyroclastic fall related to distal volcanic vents is envisaged as the dominant mechanism for the basin filling, while the pyroclastic flows and lavas are interpreted to record sporadic bigger volcanic eruptions.

Structural studies allow interpreting the original basin geometry as a half-graben, originated during a post-collisional extensional event. New and published U-Pb data establish an interval of 581 to 571 Ma for this basin and its volcanic filling. The end of the deposition was followed by the folding and metamorphism of the sequence associated with the transpressive activity of the Laguna de Rocha Shear Zone. CPO of quartz in this shear zone indicates deformation under low-temperature conditions and sinistral sense of shear. K-Ar determinations in illite fine fractions establish a minimum age limit of 524 ± 8 Ma for the latest stages of ductile deformation, in concordance with the regional trend of cooling and exhumation of the Dom Feliciano Belt.

The geochemical characteristics of the volcanic filling indicates an important crustal contribution in the magma source, with negative $\varepsilon$Nd(t), $\varepsilon$Hf(t), Meso- to Paleoproterozoic model ages, and Neo- to Mesoproterozoic inherited zircon grains. The general high-fractionated calc-alkaline nature of the compositions is similar to the geochemical characteristics of the roughly coeval granitoids from the eastern domain of the belt, which also share similarities in their isotopic signatures, suggesting common sources for both. These characteristics indicate the magmatism is autochthonous and that the volcanic vents were not located in the neighboring terranes. This observation corroborates the regional difference in which sodium-rich, high Ba-Sr, alkaline and shoshonitic signatures predominate in the western domain of the belt, with an important component of Paleoproterozoic to Archean crust in the source of the magma, while high-fractionated calc-alkaline signatures dominate in the eastern domain, with isotopic signatures that indicate a younger crust in the source of the magmas.

The Sierra de Aguirre Fm. as well as the correlated units and basins of Uruguay and southern Brazil document a regional extensional event at ca. 590 – 570 Ma in the Dom Feliciano Belt. The siliciclastic and the pyroclastic record in these basins shows predominantly continental conditions.

# Reassessing the polyphase Neoproterozoic evolution of the Punta del Este Terrane

Hernan Silva Lara[a], Siegfried Siegesmund[a], S. Oriolo[b], Mathias Hueck[a,c], Klaus Wemmer[a], Miguel A.S. Basei[c], Pedro Oyhantçabal[d]

[a]Georg-August-Universität Göttingen, Germany, [b]CONICET-Universidad de Buenos Aires, Argentina, [c]University of São Paulo, Brazil, [d]Universidad de la República, Montevideo, Uruguay

The Punta del Este Terrane is an enigmatic piece within the evolution of southwest Gondwana, and the ambiguities regarding its crustal signature allowed correlations of this block with adjacent and dissimilar domains. The Neoproterozoic pre-Ediacaran evolution of the terrane is marked by two main episodes: a large tonalitic-granodioritic Tonian magmatism, and a late Cryogenian high-grade metamorphism. Differences in the interpretations of these events result in different paleogeographic models, regarding Rodinia break-up and the assembly of southwest Gondwana. Ediacaran cover successions related to this terrane, especially the Rocha Formation and the Paso del Dragón Complex, also play a still not completely understood roll in the evolution of this terrane, and their interpretation in the evolutionary models of the Dom Feliciano Belt is ambiguous.

New isotopic data and ages from ortho- and paragneisses of the Cerro Olivo Complex indicate that the basement of the Punta del Este Terrane does not comprise large Mesoproterozoic crust but, instead, Early Neoproterozoic metaigneous and metasedimentary rocks, suggesting a Tonian retreating-mode accretionary orogen for the origin of the complex. The metasediments are roughly coeval and a large magmatic contamination due to assimilation processes is indicated by the isotopic and geochemical characteristics of the orthogneissic rocks, together with the structural relationship between ortho- and paragneisses. The isotopic data allow discarding the Nico Pérez Terrane as an important source either for the magmatism or the sediments of the Punta del Este Terrane. Instead, a correlation with the Coastal Terrane of the Kaoko Belt is proposed, based on the magmatic and metamorphic ages of both.

The new reported and discussed detrital zircon data for the Rocha Formation indicate that it was not sourced in the Dom Feliciano Belt, but in the Kalahari Craton. This conclusion reinforces the link with the Gariep Belt, being here proposed that this formation belongs to the former, and is not a counterpart in the South American side. Deposition age of the Rocha Formation is constrained between the youngest peak shown by the detrital zircon data, at ca. 660 Ma, and the beginning of the Sierra de Aguirre deposition at ca. 580 Ma, based on the structural relationship between them. This last age is also the maximum age for the accretion of the Gariep Belt to the Punta del Este Terrane. Structural analysis of the Rocha Formation indicates a progressive deformation changing from pure to simple shear. The pure shear dominated deformation took place prior to the deposition of the Sierra de Aguirre Formation, namely before ca. 580 Ma, while the simple shear dominated deformation after the end of the deposition of the former, at ca. 570 Ma. Significant strain partitioning was already operating at ca. 565 Ma.

A two-stages evolution model is considered as the most satisfactory explanation for the Dom Feliciano Belt, with an early Ediacaran collision of the Rio de la Plata and Congo cratons, succeeded by the late Ediacaran assembly of the Kalahari Craton to the former.

# Variscan fold and thrust belt of the western Harz Mountains as an analogue for a potential Enhanced Geothermal System for the University of Göttingen

Bernd Leiss, David Charles Peter Peacock, Bianca Wagner, Ali Abdelkhalek, Katherine Ford, Graziela Sosa

Georg-August-Universität Göttingen, Germany

Analogue studies of the Variscan fold and thrust belt of the western Harz Mountains are used to make predictions of an Enhanced Geothermal System beneath Göttingen, which will contribute to the existing district heating system. Kilometre- and exposure-scale field surveys, fabric characterisation, and microscale structural analyses have been undertaken to make 3D models and to provide data (Leiss et al. 2021) for recommendations for an exploration and exploitation strategy with a focus on thermal, chemical and hydraulic stimulation measures (Peacock et al. 2021a, b). Folded and thrusted slates and greywackes are the litho-structural target because such rocks are expected to occur below Göttingen. The analogue study suggests the following: (1) Veins and joints occur in both greywackes and slates, so both can be reservoir rocks. (2) Many of the veins contain calcite, suggesting that chemical stimulation would be appropriate. (3) Veins, and later joints that follow these veins, are most common in the hinges, suggesting hinge zones will be most susceptible to stimulation. (4) Those folds, veins and later joints strike $\sim NE - SE$, suggesting this will be the direction of maximum fluid flow in the sub-surface. (5) A set of master joints in the Harz Mountains strikes $\sim NW - SE$, however, suggesting this may be a potential flow direction. Information about lithologies and structures from the western Harz Mountains provided vital inputs into mechanical models that helped us suggest stimulation strategies for the Variscan rocks beneath Göttingen. In combination with the analysis of economic scenarios of the heat supplying infrastructure of the University campus (Romanov & Leiss 2021), an innovative strategy for a research well has been developed, as the first step in the exploitation of the use of deep geothermal energy for Göttingen.

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## The influence of melt-rock reactions on ultramylonite formation in the Erro-Tobbio peridotite, Italy

Jolien Linckens, Sören Tholen

Goethe-Universität Frankfurt am Main, Germany

Deformation in the upper mantle is localized in shear zones. In order to localize strain, weakening has to occur, which can be achieved by a reduction in grain size. The olivine grain size depends on the amount (grain size divided by volume fraction) of other minerals in the shear zone (i.e. pyroxenes, spinel). The other minerals can pin or drag the olivine grain boundary, hindering olivine grain growth. This process can prevent the olivine grains from growing and keep them small. In order for the other minerals to have an effect on the olivine grain size, the minerals have to be well-mixed. Different phase mixing processes have been suggested: grain boundary sliding, reactions (metamorphic, melt-rock, fluid-rock) and dissolution-precipitation creep. In addition to mixing the phases, syndeformational reactions can lead to smaller sized reaction products, which can lead to a weakening of the shear zone, when deformation is dominated by a grain size sensitive deformation process.

The importance of reactions as phase mixing and grain size reduction process depends on the geodynamic setting. For example, melts could be available in shear zones that form during rifting of the lithosphere, due to decompression melting of the asthenosphere, whereas in other geodynamic settings melts do not occur. The effect of reactions on strain localization depends on when in the shear zone evolution these reactions take place (i.e. pre-, syn- or post-kinematic). In order to assess the importance of melt-rock reactions on grain size reduction, phase mixing and strain localization, we performed a detailed microstructural analysis of spinel bearing shear zones from the Erro-Tobbio peridotite (Voltri Massif, Ligurian Alps, NW Italy). These shear zones formed during slow-ultraslow spreading in the Ligurian Tethys during pre-alpine rifting. Deformation in the shear zones occurred prior and during asthenospheric melt infiltration.

Our detailed microstructural studies show that at the first stage of deformation, clinopyroxene and olivine porphyroclasts dynamically recrystallized under melt-free conditions. With ongoing extension, silica-undersaturated melt percolated through the shear zones and reacted with the clinopyroxene neoblasts, forming mixed olivine–clinopyroxene layers. Furthermore, the melt reacted with orthopyroxene porphyroclasts, forming fine-grained polymineralic (pyroxene + olivine + spinel) layers (ultramylonites) adjacent to the porphyroclasts. Using olivine flow laws, strain rates in these layers are estimated to be about an order of magnitude higher than within the olivine-rich matrix. This contrast led to strain localization in the interconnected, ultramylonitic bands. This study underlines the importance of melt-rock reactions for grain size reduction, phase mixing and strain localization in upper mantle shear zones.

# Coupling between tectonics and magmatism – The evolution of Cer in central Western Serbia

Georg Löwe[a], Dejan Prelević[b], Albrecht von Quadt[c], Kamil Ustaszewski[a]

[a]Friedich-Schiller-Universität Jena, Germany, [b]University of Belgrad, Serbia, [c]ETH Zürich, Switzerland

The Dinarides fold-and-thrust-belt records shortening since Late Jurassic times, followed by latest Cretaceous-Paleogene collision between the Adriatic and the European-derived Tisza-Dacia Mega-units. Subsequent nappe stacking affected the Adriatic lower plate and formed a SW-verging fold-and-thrust-belt. While the external Dinarides consist of nappes derived from the Adriatic Carbonate Platform, the internal Dinarides comprise a stack of distal continental Adriatic thrust sheets and Jurassic ophiolites that are overlain by Maastrichtian trench fill sediments (termed "Sava Flysch") of the Sava suture zone. Following a phase of Oligocene I-type magmatism the internal Dinarides and the Sava zone underwent substantial extension starting in Oligo-Miocene times. This extension was concomitant with the opening of the northerly adjacent Pannonian Basin and a phase of S-type magmatism. The Cer metamorphic core complex (MCC) in central Western Serbia is located at the transition between the internal Dinarides and the Pannonian Basin and exposes a genetically heterogeneous intrusion consisting of I- and S-type magmatic rocks below an extensional mylonitic shear zone. To understand the timing between magmatism and exhumation in more detail, we conducted a U-Pb geochronological study using LA-ICP-MS on zircons from structurally and petrographically well constrained I-type and S-type granitoids in the MCC.

Our analyses show that zircons of the I-type intrusion contain several age populations: inherited cores with age maxima at approx. 270 Ma and 516 Ma, respectively, and newly formed rims with an age maximum at 31.7 Ma indicating the timing of intrusion. The S-type granite of Cer in parts reworks the I-type intrusion, as it only contains inherited cores with ages of approx. 32 Ma, while the rims show an age of approx. 18 Ma.

The total age spectrum of our data set shows strong similarities to detrital zircons found in the Maastrichtian Sava-Flysch, which indicates a mutual source for both the trench fill sediments of the Sava suture zone and the I-type magmatic rocks of the Cer MCC. Therefore, the magma giving rise to the I-type intrusion must have had a significant crustal input of Adriatic/European affinity. Furthermore, a sample of the S-type granite yielded a U-Pb (Zr) Concordia age of 17.6±0.1 Ma ($2\sigma$). Compared with a published Ar-Ar inverse isochron age of 16.6±0.2 Ma ($2\sigma$) obtained on white mica from the same sample, a cooling path of approx. 400 °C/Ma can be derived for the Cer pluton. These results contribute to the idea of rapid exhumation of mid-crustal material in the form of MCC's in response to the opening of the Pannonian Basin. Further, we show that zircons of the I-type intrusion at Cer contain significant amounts of inherited cores with an age spectrum that resembles Maastrichtian trench-fill sediments of the Sava zone. This challenges the idea that these I-type melts were generated from igneous protoliths, and rather suggests their formation from melting a Paleozoic to Mesozoic stratigraphic succession constituting tectonically buried nappes of the internal Dinarides.

# Radon anomalies in soil gas and faults in quarternary sediments – a case study from the Upper Rhine Graben using near-surface geophysical methods

Johannes Mair[a], Rouwen Lehné, Andreas Henk, Hermann Buness, Christian Hoselmann

[a]TU Darmstadt, Germany

Within the framework of the project Neotectonics in the Northern Upper Rhine Graben (NeoNORG), the relationship between fault zones in a sedimentary basin and associated radon anomalies is being investigated. The area of interest is located west of Darmstadt near the village Wolfskehlen. Radon concentrations in the Quaternary strata of the Upper Rhine Graben are generally low or moderate. However, especially neotectonic fault zones in a sedimentary basin should be indicated by an area of increased gas permeability which would result in an anomaly in the radon concentration relative to the background level. To investigate the presence of such faults, we measure the activity concentrations of radon222 along various profiles crossing the anticipated surface outcrop of fault zones using both passive and active measurement methods. Using the same profiles, various near-surface geophysical methods, i.e. electrical resistivity tomography (ERT), ground penetrating radar (GPR) and shear wave seismics, are applied to reveal the subsurface structure and potential pathways for radon migration, respectively. The ERT measurements show a range of lower resistivities in the area of the presumed fault zone. Changes in electrical resistivity in sedimentary rocks can largely be explained by their respective water content. Horizontal boundaries in the profiles of the ERT can be correlated with an adjacent research borehole of the Hessian State Office for Nature Conservation, Environment and Geology (HLNUG). It is anticipated that in the area of the fault zone, sealing clay layers separating the different groundwater levels are disturbed and thus represent an area of increased permeability. This more permeable area could also be indicated by elevated radon concentrations. So far, a 60 m shear wave profile has been measured in the frame of test measurements. In the near future a larger shear wave measurement campaign will be conducted to map structural properties of the suspected fault zone into the Pleistocene and to investigate the recent activity of the fault zone. While the combination of these various near-surface geophysical methods will allow to follow the faults to about 300 m depth, their further continuation through the sedimentary basin fill down to the crystalline basement will be traced by conventional 3D- compressional wave seismic data which was made available by an industry partner.

# 3D structural models ... and beyond

Alexander Malz, Christian Olaf Müller, Jacob Wächter, Lars Schimpf, Klaus-Jörg Hartmann, Bodo-Carlo Ehling

Landesamt für Geologie und Bergwesen Sachsen-Anhalt, Germany

In the past decades, the application of advanced geological tools like 3D modelling gained increasing interest for the spatial planning and exploitation of the subsurface. First applied to small-scale areas, their scale successively grew in accordance with high-performance processing equipment and the development of new efficient algorithms. More recently, detailed structural models of larger scales or even country- to basin-wide models were developed by research institutes and state geological surveys. Such modelling campaigns carried out by geological surveys and all participants are always accompanied with huge preparation, management and documentation efforts for the used heterogeneous data sets. Hence, building a countrywide 3D geological model is even a powerful tool for the extension, evaluation and revision of existing data. The preparation must be systematically documented and used methods must be evaluated and discussed to ensure the model's conformability. Consequently, such 3D structural modelling efforts in state geological surveys go far beyond the models itself. It is of significant importance to ensure the integration and transfer of results into modern geodata information platforms and to derive and provide clear and precise information for the broad public.

In this contribution, we will present and explain at first processes for the development of large-scale 3D structural geological models in Saxony-Anhalt, which were built in the framework of the TUNB project (Subsurface Potentials for Storage and Economic Use in the North German Basin). In that context we strongly focus on the digitalisation, evaluation, revision and documentation of data, which is used for structural modelling and model parameterization. Furthermore, we present the example of fault information to show how such information can be derived and stored in a hierarchical 'structural information system'. In our final fault database, information is stored in various levels of detail: (1) a new structural map of Saxony-Anhalt in an approximate scale of 1:200'000 and (2) detailed map sheets (scale of 1:50'000) for single fault strands and selected horizons. Every fault strand contains 3D information for footwall and hanging wall cut-offs and was systematically attributed. As a consequence it became possible to derive geometries, timing and kinematic information for every scale. This shows the enormous potential of 3D modelling in modern geological surveying towards sustainable and comprehensible information. In the future, 3D modelling will also need to quantify the predictive power (or uncertainty) of the model (similar to fact maps in mapping).

# The Subhercynian Basin in Saxony-Anhalt (Central Germany) - Results from 3D structural modelling

Alexander Malz[a], Christian Olaf Müller[a], Jacob Wächter[a], Charlotte Kühnast[b]

[a]Landesamt für Geologie und Bergwesen Sachsen-Anhalt, Germany, [b]Martin-Luther-University Halle, Germany

The Subhercynian Basin in Saxony-Anhalt (Central Germany) is defined as that area which is located between the basement uplifts of the Harz Mountains in the south and the Flechtingen High in the north. Its recent complex structural configuration is the result of several tectonic events in Mesozoic times. During Late Triassic and Late Jurassic/Early Cretaceous times, E-W and NE-SW extension lead to the separation of the area into several blocks separated by deep-ranging normal faults. In some areas these movements affected the migration of Late Permian (Zechstein) salt and salt pillows evolved. In Late Cretaceous times, the entire area became compressed leading to the reverse reactivation of normal faults, the development of new thick-skinned and thin-skinned thrust faults, the uplift of adjacent basement highs and subsidence of deep foreland basins in the south. With the end of Late Cretaceous contraction, the entire area became uplifted and the resulting structural configuration strongly influenced later (Cenozoic) sedimentation.

In this contribution we present the results of a large-scale 3D structural modelling campaign carried out at the geological survey of Saxony-Anhalt. Therefore, we prepared approximately 80 interpreted seismic reflection sections in the depth domain, some hundreds of deep boreholes and interpolated depth maps. Based on these data fault strands were correlated to complex fault zones. Fault kinematics was derived from thickness distributions of selected stratigraphic units. Afterwards, the correlated fault network formed the basis for the implicit modelling using the 'Structure and Stratigraphy' (SnS) workflow of Gocad/SKUA, which was applied to the complete stratigraphic succession from the base Zechstein to the Late Cretaceous. For younger horizons (base Cenozoic and base Rupelian), depth maps and all available (shallow) boreholes were used for 2D interpolations in a geographic information system, which were later transferred into the 3D modelling environment.

The resulting 3D structural model comprises 13 stratigraphic horizons, all regional fault zones and two salt structures. It forms the first uniform structural 3D model for the research area and can now be used for large-scale regional planning efforts as well as structural, kinematic and regional geological interpretations.

# Structural and tectonic evolution of the Cadomian wallrock of the Melibokus Pluton (Odenwald, Mid-German Crystalline Zone)

Henri Paul Meinaß[a], Matthias Hinderer, Eckardt Stein

[a]TU Darmstadt, Germany

The metamorphic wallrock of the Variscan Melibokus Pluton (also known as "Balkhäuser Schiefer") is exposed in a NNE-SSW oriented zone in the westernmost part of the central Odenwald Crystalline Complex. According to the current state of research, these rocks are the oldest in the state of Hesse with a Late Ediacaran to Lower Cambrian age. They are interpreted as a metavolcano-clastic sequence and are part of the Cadomian basement in the Odenwald Crystalline Complex.

Petrographically, the formation is composed of biotite-plagioclase-gneiss with intercalated biotite-hornblende schists, quarzites, amphibolites and calc-silicate rocks. This rock sequence is intruded by granitoid dykes as well as by pegmatitic and aplitic veins. The Melibokus wallrock was deformed under ductile conditions during the Cadomian orogeny. The metamorphic foliation planes strike NNE-SSW and dip steeply ESE, which is in contrast to the commonly observed NE-SW striking foliation of the Variscan basement in the Odenwald Crystalline Complex. They are crosscut by granitoid dykes with Lower Cambrian intrusion age according to U-Pb zircon dating. Therefore, this deformation phase can be considered to be Precambrian. Observations in the field and stereographic projections point to at least one more ductile deformation phase accompanied by tight to isoclinal folds with eastward plunging fold axes.

During the Paleogene the Melibokus wallrock underwent a number of brittle deformations, which can be related to the formation of the nearby Upper Rhine Graben. NNE-SSW striking strike-slip faults and normal faults dissect the basement into several tectonic blocks. Comparison with large-scale paleostress fields and the occurence of an Eocene basalt within the Melibokus wallrock suggest faulting during the initial stage of the Upper Rhine Graben during the early Paleogene. The brittle deformation could be integrated into a model of a NNE-SSW oriented pull-apart basin or extensional strike-slip duplex, which could explain today‘s anomalous geometry and position of the Cadomian basement rocks within the Variscan units.

# New evidence on the setting of the Pretzsch-Prettin Crystalline Complex (Germany) by 3D gravity and geological modelling

Christian Olaf Mueller, Jacob Wächter, Alexander Malz

Landesamt für Geologie und Bergwesen Sachsen-Anhalt, Germany

High-grade metamorphic and plutonic rocks in crystalline complexes developed at former suture zones and are key elements in understanding regional plate tectonics. Additionally, they are of increasing interest as resource material (geothermal energy generation, deposit) and host rock for radioactive waste. The Pretzsch-Prettin Crystalline Complex (PPCC, Saxony-Anhalt, Germany) as part of the Mid German Crystalline Rise is one example of a late-orogenic intrusion in the former Rheic Suture Zone. Former 2D geophysical investigations focussing on the setting and outline of the PPCC remained ambiguous. The results are mostly limited to broad seismic reflective transition zones and magnetizations and densities of similar scale. Hence, their interpretation require evidence from other geoscientific disciplines. Recently, we applied a 3D geophysical and geological modelling by additionally integrating petrographic results from lab analyses to gain new insights into the characterisation and formation history of the PPCC.

3D forward and inverse gravity modelling was performed based on seismic reflection and refraction data, gravity data and borehole data. Wavelength filtering and 3D Euler Deconvolution applied to the gravity data provided additional evidence on the local fault system and main gravity anomalies. The gravity stripping technique was used for the separation of the gravity signal of the basement. Subsequently, density measurements at rock samples and results on rock composition from thin sections were linked to the modelled density zones of the basement and were accounted for in the modelling process.

The study revealed first evidence to a northward extent of the PPCC from the area of uplifted basement at the Flechtingen High into the North German Basin. The derived map of regional basement topography shows a prominent escarpment of up to 2.5 km along the Wittenberg Fault, marking the transition into the basin. The PPCC itself is characterized by comparable low densities of $2.63 \pm 0.03$ g/cm$^3$ consisting of monzogranites and granodiorites, supported by a prominent low within the gravity signal of the basement. Monzogranites to quartz monzodiorites of up to 20% biotite and amphibole with higher densities are modelled in the surrounding area. In this regard, our gravity modelling study provided new insights into the spatial distribution of deep-seated crystalline rocks of different composition and gained information about the mineral content of yet poorly investigated rocks from the outer rim of the Mid German Crystallin Rise. Upcoming studies with a similar approach might proof a continuation of this crystalline complex towards adjacent ones within the Mid German Crystalline Rise, which would have main impact on understanding its formation history.

# 3D gravity and geological modelling in the Subhercynian Basin (Germany) – A strategy for enhanced modelling of the basin's sedimentary and crustal setting

Christian Olaf Mueller, Jacob Wächter, Alexander Malz
Landesamt für Geologie und Bergwesen Sachsen-Anhalt, Germany

3D geological modelling in highly complex or less explored areas is always affected by conceptual uncertainty. Recent studies have shown, that the integration of gravity data to the modelling process is a powerful tool to reveal additional information on the regional geological setting and to significantly reduce a model's uncertainty. However, gravity modelling itself underlies the non-uniqueness problem, indicating that always more than one model is consistent with the observed gravity field. Consequently, a cross-validation of gravity models by integrating regional concepts, geometric and kinematic construction methods and restoration techniques should be included in the modelling concept.

In this regard, we defined an integrated gravity and geological modelling strategy, which starts with extracting a-priori information from geological maps, 2D seismics, borehole data and their independent analysis and conservative interpretation. Subsequently, the gravity data is analysed by wavelength filtering, gradient calculation and 2D Euler deconvolution and is combined with the geological interpretations. The resulting dataset is validated by 2D cross-section balancing techniques considering bed-lengths and area consistency. The obtained serial balanced cross-sections served as a solid basis for 3D gravity modelling. We applied this integrated workflow to the less explored eastern part of the Subhercynian Basin (Saxony-Anhalt, Germany) and its transition to the Mid German Crystalline Rise. Herein, we observed that combining the independently and partly ambiguous data allows the generation of new insights into the geological setting, especially the local fault system, outline of salt structures, extent of anticlines and synclines as well as the characterization of the basement.

# The anisotropic properties of granites – discussing a workflow for a case study

Franz Müller[a], Peter Hallas[b], Uwe Kroner[a]

[a]TU Bergakademie Freiberg, Germany, [b]Thüringer Landesamt für Umwelt, Bergbau und Naturschutz, Weimar, Germany

For permanent nuclear waste disposal sites, crystalline rocks, especially granite, are considered appropriate host rocks. The crystalline basement of Germany consists of pre-, syn- and post-Variscan felsic plutons, which were consolidated during different tectonic regimes. It is expected that the tectonic environment during intrusion influenced the material properties. Hence, we will conduct a systematic study to investigate the fabric of such plutonic rocks. The focus will lie on the primary anisotropy that developed during the emplacement and crystallization of the rocks. Furthermore, the relation to late- and post magmatic processes such as hydrothermal activity and brittle deformation, i.e. the secondary anisotropy, will be investigated.

To characterize the primary anisotropy, Shape Preferred Orientation (SPO), Crystallographic Preferred Orientation (CPO) and mineral chemistry are analyzed side by side. Whole rock textures will be used to model petrophysical properties, which allows us to compare actual measurements and modeling results. The secondary anisotropy is investigated by systematically mapping late- to postmagmatic annealed microcracks and open fractures.

Measurements of the anisotropy of magnetic susceptibility (AMS) and diffraction experiments (neutron time-of-flight) reveal the fabrics and textures of entire rock volumes. Furthermore, we obtain spatially resolved data from the composite digital image analysis of microscopy, mineral liberation analysis (MLA), cathodoluminescence (CL) and electron backscatter diffraction (EBSD). For comparability, it is essential to interpret the results of all measurements in a common spatial reference system, i.e. the geographical reference frame. We develop a method to sustainably retrace multiple rotational procedures during sampling, sample preparation and measurement. For a large number of samples and measurements, complete traceability of all investigation steps is of major importance. Therefore, all data is organized within a relational database with GIS integration.

# Taking the pressure out of Archean Metamorphism: The role of $CO_2$ in assessing metamorphic conditions of the Isua supracrustal belt, W-Greenland

Thomas Müller[a], Dominik Sorger, Jiawei Zuo, Alexander Webb, Anthony Ramirez-Salazar, Sandra Piazolo

[a]Georg-August-Universität Göttingen, Germany

The Eoarchean Isua Supracrustal Belt (ISB), West Greenland exposes one of the oldest rock records on Earth. Its tectonic setting is still a subject of debate, with interpretations ranging from plate tectonics to environments that are dominated by vertical tectonics including for example a heat-pipe model. Information on the origin and metamorphic P-T-X evolution of ultramafic lenses exposed in the Western part of the ISB may shed light on its geodynamic evolution. Geochemical signatures are non-conclusive in view of their origin, whereas cumulates are favored over mantle rocks. A cumulate origin is consistent with all geodynamic models proposed, yet this information cannot help to distinguish between these models. In contrast, determining the metamorphic pressure that these lenses have experienced promises to be more conclusive in terms of possible geodynamic models. In the literature, there is a general agreement of high to ultrahigh pressure conditions for the metamorphic overprint based on the presence of titanian clinohumite und titanian chondrodite, i.e., phases typically reported to indicate high to ultrahigh pressure metamorphism of ultramafic rocks.

Textural inspection of a dunite sample from one of the Isua ultramafic lenses reveals clear evidence of an olivine breakdown reaction to form antigorite+magnesite+Fe-oxide associated with the occurrence of Ti-humites. The presence of carbonate instead of brucite highlights the role of $CO_2$ and focusses attention to the need to accurately describe phase relations for the metamorphic evolution of these ultramafic rocks. In this contribution, we present results assessing the role of $CO_2$ using a combination of textural analysis and thermodynamic calculations. It is shown that the stability fields of the observed mineral assemblage are strongly controlled by the fluid composition ($XCO_2$). Here, high to ultrahigh pressure conditions (> 2 GPa) contrasting the homogenous amphibolite PT conditions of the Eastern part of the ISB are indeed possible, but limited to a very narrow range of fluid composition. However, thermodynamic modelling of phase relationships both as Schreinemarker analysis and isochemical phase diagrams reveal that the formation of the observed reaction textures including the formation of the Ti-phases can be readily achieved with a broader range in fluid compositions via cooling at amphibolite facies conditions (580 to 500 °C at 1 GPa) in the presence of a $CO_2$ -bearing fluid in agreement with the PT conditions determined for the rest of the ISB. Hence, the general wisdom of Ti-clinohumite and Ti-chondrodite being unequivocal indicative of high to ultrahigh pressure conditions in ultramafic rocks has to be abandoned at least if there is a clear indication of the presence of $CO_2$ -rich fluids.

In summary, our results point to a lack of evidence for higher pressure conditions experienced by these ultramafic lenses. Consequently, implied lower pressure conditions remove a strong argument for the ISB as a well-defined result of a plate tectonic setting, and permits other tectonic settings, such as a proposed heat-pipe model, as viable alternatives.

# Thermobarometry at extreme conditions - an example from NE Greenland

Thorsten Nagel[a], Kathrin Fassmer[b]
[a]Aarhus Universitet, Denmark [b]University of Innsbruck, Austria

We present eclogites and garnet pyroxenites from Danmarkshavn (Greenlandic Caledonides). So far, one ultra-high pressure (UHP) location has been described from NE Greenland. There, thermobarometry yielded conditions of 972 °C/36 kbar (Gilotti and Ravna, 2002).

Eclogites from Danmarkshavn show spectacular exsolution of Qtz from Cpx, which is known from several UHP locations. The sample most suitable for unraveling precise conditions, however, is a garnet pyroxenite containing abundant Cpx and Opx, some Grt, minor accessory minerals as well as little retrograde Am and Pl. Opx and Cpx preserve high-pressure compositions in cores of large crystals and extremely low Al-content in Opx clearly indicate UHP conditions. A considerable portion of these minerals, however, reequilibrated during exhumation with especially Cpx showing complex retrograde zoning. We infer that Grt grains completely reequilibrated during net-transfer reactions producing Am and Pl.

Precise conditions in such rocks are often achieved by intersection of isopleths, e.g. Al-in-Opx with Grt-Cpx-Mg-Fe thermometry. Both isopleth sets have positive slopes in pressure-temperature space. If exhumation occurs along a trajectory steeper than the thermometer isopleth, equilibration of Mg-Fe-exchange during exhumation leads to possibly dramatic overestimation of peak conditions. In our sample, this yields up to 1000 °C/ $>$ 40 kbar. Based on Cpx and Opx core compositions alone, however, we infer considerably lower peak conditions of 800-830 °C/30-32 kbar. We find that micro-xrf scans of whole thin sections yield powerful data on mineral zoning, reaction progress and the degree of reequlibration. Such maps allow better defining targets for high-resolution mapping and high-precision microprobe work.

Lu-Hf-Grt-whole-rock dating of the eclogite sample yields an age of 357.8 $\pm$ 1.7 Ma, considerably younger than Caledonian nappe stacking and even postdating postcaledonian basin formation. The age is, however, consistent with zircon ages from the other UHP location in NE Greenland and we interpret it as dating peak pressure conditions or cooling shortly after peak pressure conditions. Exhumation occurred in a continent-scale, high-metamorphic, right-lateral shear zone, the Germania Land deformation zone. This enigmatic metamorphism and deformation cannot be explained in the context of caledonian orogeny, but requires a major addition to the tectonic history of NE-Greenland (see contribution of Kroner and Nagel, TSK19).

# Microphysical controls on earthquake nucleation: experiments, microstructures and models

Andre Niemeijer
Utrecht University, Netherlands

Earthquakes nucleate within the seismogenic zone typically under hot and wet conditions. Earthquake nucleation requires fault friction to decrease with increasing sliding velocity, i.e. to have so-called velocity-weakening properties, quantified using the empirical parameter rate-and-state friction (RSF) (a-b). In numerical simulations of the seismic cycle, the seismogenic zone is delineated by a negative value of (a-b) which is assumed to be a material property. In this contribution, I will present experimental data on the frictional properties of various simulated fault gouges and microstructural observations which demonstrate the crucial role of fluid-rock interactions in controlling the temperature range at which earthquakes can nucleate, i.e. how they control the depth range of the seismogenic zone. The experimental data show that the velocity dependence of friction, i.e. (a-b), is itself dependent on velocity under hydrothermal conditions. Three regimes of velocity dependence can be identified, with transitions from velocity strengthening to weakening and back to strengthening which occur due to either an increase in loading velocity at constant temperature or due to an increase in temperature at constant velocity. A variety of fault gouges with variable composition show this behaviour. Microstructural observations suggest that fluid-assisted mechanisms where active in the low velocity or high temperature regime. In contrast, high velocity or low temperature microstructures show evidence for fracturing and grain sliding / rotation, resulting in a chaotic, cataclastic and porous microstructure. I will present a microphysical model, based on an idealized microstructural grain arrangement which is able to predict the experimentally observed transitions in velocity-dependence of friction with temperature and velocity. Central to the model is the competition between time-dependent compaction and slip-dependent dilatation. The model equations have similarities with RSF equations, but with porosity as a state variable with a physical basis. Simulations of heterogeneous fault behaviour over large time-scales show slip events that cover the entire spectrum of fault slip, from aseismic slip through slow-slip to seismic events. In addition, they predict the possibility of large, fault-spanning ruptures on faults that are otherwise seismically quiescent. The input parameters of the microphysical model have a physical meaning and can be constrained by a combination of field observations and geochemical data on solubility and dissolution/precipitation kinetics of minerals.

# Testing fission-track tectonics: A natural long-term, low-temperature annealing experiment in Palaeozoic basement

Lucie Novakova[a,b] Raymond Jonckheere[b], Bastian Wauschkuhn[b], Lothar Ratschbacher[b], Carolin Aslanian[b]

[a]IRSM, Czech Academy of Science, Prague, Czech Republic, [b]TU Bergakademie Freiberg, Germany

An important part of geological research is concerned with the architecture of the earth's crust and the processes that created it. The fission-track method is one of several geochronological methods that provide numerical constraints on the timings, rates and magnitudes of these processes. Fission tracks in apatite are $\sim$ 20 $\mu$m long and $\sim$ 10 nm wide, too thin to observe with an optical microscope. Polished grain mounts must therefore be etched to make them visible. It is generally taken for granted that factors related to polishing, etching, counting and measuring the etched tracks are inconsequential. We believe that, from lack of investigation, there persist certain misconceptions regarding these issues, which lead researchers to overestimate the accuracy of the track counts and length measurements. Knowledge of the true effective time of confined tracks based on measurements of their widths presents a potential improvement in modelling the thermochronological conditions of the studied samples.

It is nevertheless not certain that reliable tectono-thermal histories are obtained with this development. This must be established based on well-constrained field data. The 9.1 km KTB borehole drilled into the western border of the Bohemian Massif is an ideal test site for temperatures up to 265 °C (Wauschkuhn et al., 2015). The Naab Mountains, 40 km to the south, were exhumed in the Variscan and never covered by more than 1 km of sediments since the beginning of the Permian (Vercoutere, 1994). Samples from the Palaeozoic basement, again exposed at the surface, have thus never experienced temperatures in excess of $\sim$ 40 °C. This makes the Naab a perfect testing ground for the low-temperature predictions of fission-track modelling, in this case on basement samples with uniform lithologies rather than on ocean bottom samples containing apatites of different origin (Spiegel et al., 2007).

We modelled our samples using the multikinetic annealing model and the HeFTy program (Ketcham et al. 1999; 2005). The Naab thermal histories exhibit significant differences for different etch-time intervals, demonstrating that the experimental conditions have a decisive influence on the geological models. The etch time effect can however be undone by adjusting other model parameters, specifically the so-called zero-length, i.e. the reference mean length of tracks that have not been annealed. In particular in connection with this parameter, there exist different approaches: using the overall default, the length corresponding to the specific composition of the investigated apatite, if known, that measured on a standard containing induced fission tracks produced by fission or 235U in a nuclear reactor, or that corresponding to the same etch-time window as the fossil track measurements (Novakova et al., 2021). We report results on parameter settings that produce modelled burial and exhumation histories for the Naab samples consistent with the geological evidence.

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# Tectonic setting of Cretaceous synorogenic sediments of the Austroalpine (Eastern Alps): From thin-skinned foreland thrust belt to oceanic subduction

Hugo Ortner, Anna-Katharina Sieberer
University of Innsbruck, Austria

Numerous models have been proposed to explain the tectonic setting of synorogenic sedimentation in the Cretaceous Eastern Alps (Lech-, Rossfeld-, Losenstein-, Branderfleck Fms., Gosau Group), which are (i) tectonic erosion or (ii) roll back during oceanic subduction, and (iii) growth of a foreland thrust belt. So far, no model was able to explain all of the following aspects:

- Synorogenic sedimentation developed conformably from deep marine passive margin sediments.
- Synorogenic deposition started during continental conditions where parts of the orogenic wedge were uplifted. These units subsided to the neritic zone first, then to abyssal depths. In the Northern Calcareous Alps (NCA), synsedimentary deposits from below the CCD can be found.
- In the internal part of the Alpine wedge, synorogenic sediments are found in the hanging wall of major normal detachments. In the external part of the wedge such detachments are not observed, but growth strata or sediment accumulation occur in tear fault-related depocenters of a contractional setting.

A major problem is the observation of shortening and subsidence at the same time. Subsidence shifts from the NW to the SE in the NCA.

According to Stüwe and Schuster (2010), Cretaceous orogeny in the Eastern Alps initiated when subduction started along an intracontinental transform fault. Thrusting propagated across the Austroalpine and reached oceanic crust at the turn from Early to Late Cretaceous, when the crystalline basement of the NCA was likely being subducted and replaced by oceanic crust. Using such a scenario, we describe the tectonic setting of Cretaceous synorogenic sediments as follows:

1) Synorogenic sedimentation started in a deep marine environment inherited from Jurassic passive margin formation.

2) Thickening related to nappe formation caused uplift of the nappes and thus short-lived continental conditions.

3) The external Austroalpine wedge was affected by subsidence caused by replacement of continental basement by oceanic crust. The surface of typical oceanic crust is located in a depth of 4.5 km (e.g., Kearey et al., 2009). The surface of an isostatically supported $1 - 10$ km thick wedge on oceanic crust would be in a depth of $3.9 - 2.9$ km. The internal Austroalpine, where basement is preserved, is not affected by this major subsidence.

Subsidence pulses would be observed if the Austroalpine was dissected by transform faults, that separated thinned continental crust from the continent. The existence of such transform faults within the NCA has recently been suggested by Ortner and Kilian (2021) and Sieberer and Ortner (submitted).

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# Deformation of a mountain-sized olistolith: An example of raft tectonics from the Northern Calcareous Alps (NCA) of Salzburg

Hugo Ortner[a], Christoph Ganser, Michael Stipp[b]
[a]University of Innsbruck, Austria [b]Martin-Luther-Universität Halle-Wittenberg, Germany

Passive and active continental margins are sites of emplacement of huge slides and olistoliths. In most cases, some kind of tectonic process leads to mobilization of large blocks of the sedimentary succession. If these continental margins are involved in an orogeny at a later stage, it may be difficult to distinguish very large slides from nappes.

We studied deformation at the base of the Schwarzer Berg olistolith that has a thickness of 1.5 km and several km length and width. It consists of Triassic limestones and dolomites, and a discontinuous carpet of evaporitic shales and cellular dolomites (Permian Haselgebirge) at the base. It was emplaced into Late Jurassic pelagic siliceous shales of the Lower Juvavic Lammer zone of the Northern Calcareous Alps south of Salzburg. Cross sections of the olistolith demonstrate that the basal carpet is flat, but an internal anticlinal structure exists within the olistolith on top. Both limbs are truncated at the level of the carpet.

The basal contact of the Olistolith to the Jurassic pelagic siliceous shales is characterized by the absence of major and pervasive macroscopic deformation features. It is an irregular, wavy surface. Locally, the lower viscous sediments are injected into the higher viscous dolomite of the olistholith. This interface resembles a mullion-type structure. The cusps are m-scale and filled with the Jurassic shales where the olistolith rests on the Jurassic, or several m-scale and filled by Permian Haselgebirge shales, where the dolomite is in contact to the Permian within the olistolith. Especially the large cusps are strongly asymmetric and tilted to the east.

On the microscopic scale, cataclastic deformation is observed in the Triassic dolomites at the base of the olistolith, and in the uppermost calcareous layer of the Jurassic, but not in the Jurassic deposits below. There, deformation features are almost absent corresponding to the field observation. Right below the contact in the Jurassic siliceous shales cm-scale verging folds occur. In a calcareous layer 50 cm below the contact, bookshelf structures are found, in another layer 80 cm below the contact brecciated clasts occur. All structures allow to deduce a transport direction towards the E.

The structural inventory can be related to three different stages of structural evolution: The km-scale antiformal structure resembles the geometry of a mock-turtle anticline that might have developed during (1) breakaway of the olistolith. The absence of pervasive deformation at the base of such a large olistolith points to (2) transport of the olistolith on a layer of overpressured fluid, or a Haselgebirge salt pillow. In the first case, fluid pressure must have been high enough to support the olistolith. The existence of asymmetric mullion-like structures documents simple shear and traction at the base of the olistolith. This requires fluid pressure release and (3) grounding of the olistolith, associated with formation of mullions, folds and bookshelf structures.

# Use of Mohr diagrams to predict fracturing in potential geothermal reservoirs

David Charles Peter Peacock[a], David Sanderson, Bernd Leiss[a]
[a]Georg-August-Universität Göttingen, Germany

Inferences have to be made about likely structures and their effects on fluid flow in a geothermal reservoir at the pre-drilling stage. Simple mechanical modelling, using reasonable ranges of values for rock properties, stresses and fluid pressures, is used here to predict the range of possible structures that are likely to exist in the sub-surface and that may be generated during thermal and hydraulic stimulation of geothermal reservoirs. In particular, Mohr diagrams are used to show under what fluid pressures and stresses different types and orientations of fractures are likely to be reactivated or generated. The approach enables the effects of parameters to be modelled individually, and for the types and orientations of fractures to be considered. This modelling is useful for helping geoscientists consider, model, and predict the ranges of mechanical properties of rock, stresses, fluid pressures, temperatures, and the resultant fractures that are likely to occur in the sub-surface. Here, the modelling is applied to folded and thrusted Variscan greywackes and slates, which are planned to be developed as Enhanced Geothermal Systems beneath Göttingen (Germany) and at Havelange (Belgium).

## A model for joints that post-date folding

David Charles Peter Peacock, Bernd Leiss
Georg-August-Universität Göttingen, Germany

Joints are commonly modelled using their orientations relative to folds, with their kinematics interpreted based on the stress system in which the fold developed. Such models make tacit or explicit assumptions that joints form during folding. It is common, however, that the folds are associated with faults, veins and cleavage, with these being crossed or followed by later joints. A model is presented for joints that post-date folding, based on observations from Liassic limestones and shales of the Bristol Channel Basin (UK), and from Palaeozoic metasedimentary rocks of Cornwall (UK) and the Harz Mountains (Germany). A set of relatively long and straight "master" joints is commonly observed, and it is suggested that the orientations of these are controlled by interactions between far-field stresses, folds, bedding and such pre-existing structures as faults, veins and cleavage. In some cases, master joints curve as they cross folds. A second set of joints can commonly be recognised, these abutting and therefore post-dating the master joints. Other, later joints typically show a wide range of orientations, these developing in the highly anisotropic stress system between the earlier joints. Joints from any of these sets commonly follow pre-existing structures, which can cause members of different joint sets to cross-cut each other, making it difficult to determine age relationships. This tends to mean that the pattern of joints is more difficult to interpret in rocks with higher strains and more pre-existing structures.

This model is based on more realistic interpretations of the age relationships and mechanics of the structures. It can therefore stop incorrect assumptions being made when building reservoir models, such as that the distributions of open fractures are related in a simple way to fold curvature or strain.

# Models for the origins of chaotic meta-sedimentary rocks in the Harz Mountains, Germany

David Charles Peter Peacock, Bernd Leiss
Georg-August-Universität Göttingen, Germany

Chaotic units of Palaeozoic metasedimentary rocks in the Harz Mountains have been attributed to Early Carboniferous submarine mass-flow processes (i.e. olistostromes) or the chaotic rock fabric mainly developed by "brittle-ductile" Variscan (Late Carboniferous) deformation. These models are discussed and a third model is introduced, this involving remobilisation of overpressured, undercompacted shales during Variscan folding and thrusting. In this third model, sandstones, limestones and cherts were lithified by mechanical and chemical compaction during burial, but the shales were not lithified during burial because they were overpressured. The onset of Variscan contraction caused cleavage to develop in the lithified sediments, with the shales becoming increasingly overpressured. This led to injection of the shales into faults and extension fractures in the lithified sediments, and the development of breccias and "block-in-matrix" fabrics. The shales became lithified when the fluids were able to escape and the fluid pressure dropped (i.e. they changed from having the properties of a soil to having the properties of a rock). A slaty cleavage eventually developing as Variscan contraction and metamorphosis continued. It is possible that each of these three models are correct, but are applicable for different times.

Present-day evidence for the existence of overpressured, undercompacted shales at depths of several kilometres includes mud volcanoes.

## A closer look a feather features in quartz as differential stress indicators in the shock wave

Michael H. Poelchau
Albert-Ludwigs-Universität Freiburg, Germany

During the impact cratering process, a shock wave in generated by the impacting projectile that deforms the target rocks. While there is a large hydrostatic pressure component within these shock waves, differential stresses of up to 1-2 GPa can occur. In planar shock waves formed e.g. in experiments, it can be assumed that stress and strain are coaxial, leading to pure shear deformation. However, numerical modeling indicates that there is a non-coaxial component of strain leading to subsimple shear and vorticity (Rae et al. 2021). The amount of these components varies based on the distance and depth relative to the point of impact, and can also increase within a sample as the shock wave passes through.

In a previous study by Ebert et al. (2021) the orientations of microstructural deformation features were measured in order to constrain the compressional axis of the shock wave. These were i) conjugate systems of grain-scale micro-shear faults found in quartz, termed "feather features" (FFs), consisting of a shear plane and well-ordered subsidiary fractures to one side, ii) Brazil twins that form through shearing along the basal plane in quartz, and iii) kinked biotites. These features were found in shocked granites of the peak ring of the Chicxulub impact crater in Yucatán, Mexico, which was drilled by IODP/ICDP Expedition 364. Results of this study show a general agreement of the compressional axes to within 30° indicating the three microstructures formed under the same stress-strain regime within the shock wave.

Many issues and questions remain with regards to the nature of feather features. While $\mu$m-scale displacements have been observed that usually coincide with the implied shear orientation of the FFs, often no displacement is discernable. This appears to be more common in crystalline rocks than in porous sandstones. Furthermore, FFs have occasionally been observed to lie completely within single grains of quartz. In rare cases FFs can be seen with subsidiary fractures on both sides, indicated a reversal of shear directions. The lack of a systematic study needs to be addressed, and I will attempt to compile data from several craters for this study.

A recent field trip to the Araguainha structure in Brazil revealed a surprisingly high density of FFs within quartzite clasts of conglomerates near the structure's center. This is ideal for a true 3D study of FF orientations within a single sample using three perpendicular thin sections. Initial results show a larger range of FF orientations compared to Ebert et al. (2021). A more detailed study will be made, and I intend to apply fault slip analysis to the results to verify if and how well FFs can constrain a compressional axis. The results should help to deepen our understanding of deformation processes within the shockwave.

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## Deformation in front of and within the Dolomites Indenter

Hannah Pomella[a], Anna-Katharina Sieberer[a], Thomas Klotz, Hugo Ortner[a]
[a]University of Innsbruck, Austria

The tectonic architecture of the European Alps is significantly influenced by two factors: on the one hand, two orogenies are superimposed, the Cretaceous and the Cenozoic. On the other hand, the N(NW)-directed indentation of the Adriatic microplate from latest Eocene onwards causes striking lateral differences in deformation. As clearly seen in map view and digital elevation models, the Adriatic Indenter is subdivided into a western and an eastern sector. These subdomains are termed Canavese-Insubric Indenter (W) and Dolomites Indenter (E), and are characterized by contrasting deformational styles and histories. The northern border of the Adriatic Indenter, the approximately E-W oriented Periadriatic fault system, is offset by the NNE-SSW-trending sinistral-transpressive Giudicarie fault system (GFS) at the transition between the two subdomains.

The sinistral-transpressive GFS is active from late Oligocene on (Müller et al., 2001; Pomella et al., 2011) and has accumulated a total offset of $\sim$ 75 km in map view during various deformational phases. The N(NW)-directed movement of the Dolomites Indenter modifies the early Cenozoic nappe structure of the Alpine orogen. The accommodated shortening changes substantially, depending on the oblique shape of the indenter and its counter-clockwise rotation. During Neoalpine indentation, the Austroalpine Basement units northwest of the GFS experienced open folding of the Cretaceous nappe stack only and preserved Cretaceous metamorphic ages. In contrast, the previously deep-seated Neoalpine metamorphic Subpenninic and Penninic units of the Tauern Window in front of the Dolomites Indenter's tip are exhumed and the Austroalpine units adjacent to the Indenter are brought into a subvertical or even overturned position (e.g., Pomella et al., 2016).

Fission track data from the Tauern Window and the Austroalpine units, directly adjacent to the north-western corner of the Dolomites Indenter, indicate cooling below the Zircon Fission track annealing zone (180-200 °C) in the Early Miocene and below the Apatite Fission track annealing zone (60-100 °C) in the late Miocene (Pomella et al., 2012; Bertrand et al., 2017 and citations therein). Fission Track and (U-Th)/He on Apatite data, derived from a horizontal section of the Brenner Base Tunnel and reaching from the Dolomites Indenter into the Austroalpine nappe stack, indicate continuous differential uplift of the northern block along the, in this area, approximately E W striking Periadriatic fault system until the Pliocene (Klotz et al., 2019).

Earthquake focal solutions and satellite-based geodetic studies show, that indentation is ongoing today with an overall convergence rate of 1–2 mm/year between the counter-clockwise rotating Adriatic and stable European plate, respectively (e.g., Metois et al., 2015). The significant present-day seismotectonic activity concentrates in the Friuli area in the southeast, whereas there is currently neither significant seismicity along the western and northern boundaries of the Dolomites Indenter nor in the northerly adjacent Austroalpine basement and the Tauern Window. Increased seismic activity can only be detected north of the Tauern Window along and north of the Inn Valley (Reiter et al., 2018; Oswald et al., 2021). Based on field evidence and thermochronological record, the recent seismic distribution indicates an important change in style and localisation of deformation compared to what is documented from the past.

Not only knowledge of the deformation in front of the Dolomites Indenter and along its boundaries is important for understanding crustal-scale processes during Alpine orogeny, but also of its internal deformation. However, this area has been studied far less intensively in this respect to date and comprehensive thermochronological data is lacking entirely. Our approach to unravel the exhumation and deformation history within the Dolomites Indenter is a combination of compilation and acquisition of detailed structural field data, collection of a new and comprehensive low-temperature thermochronological dataset, and crustal- to lithospheric-scale physical analogue modelling experiments.

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# Finding Quaternary earthquake activity by dating fault gouges via trapped charge methods: The case of the Eastern Periadriatic Fault System

Erick Giovanni Prince Gutierrez[a], Kamil Ustaszewski[a], Sumiko Tsukamoto[b], Christoph Grützner[a], Marko Vrabec[c]

[a]Friedrich-Schiller-Universität Jena, Germany, [b]LIAG Hannover, Germany, [c]University of Ljubljana, Slovenia

Optically stimulated luminescence (OSL) and electron spin resonance (ESR), often referred to as trapped charge dating methods, are widely used in Quaternary science, archeology, and most recently in dating past seismic events. Their physical principle is the accumulation of unpaired electrons in lattice defects of quartz and feldspar. These defects are caused by the natural radiation produced by the decay of radiogenic nuclides. When heated, these unpaired electrons release a luminescence signal, and the system is (partly) reset (Fukuchi 1992, Aitken 1998, Tsukamoto et al., in Tanner 2019). In our case, we investigate the heat caused by earthquakes due to shear heating. Trapped charge methods are especially useful for dating Quaternary earthquake activity at near-surface conditions due to their dating range (a few decades to $\sim$ 1 Ma) and low closing temperature. The Periadriatic Fault System (PAF) is among the most important post-collisional structures of the Alps; it accommodated between 150-300 km of right-lateral strike-slip motion between the European and Adriatic plates from about 35 until 15 Ma. Still, the absence of historical and instrumental seismicity related to the fault is intriguing, especially when compared to nearby structures in the adjacent Southern Alps. Through this project, we aim to date fault gouges produced by the eastern PAF system, to show which segments accommodated seismotectonic deformation during the Quaternary. We intend to measure single grains of quartz and feldspar via OSL and quartz for ESR, using samples with grains diameters of 100-250 $\mu$m and less than 100 $\mu$m, to provide a comprehensive analysis and to study the effects produced by variations in the grain sizes. During our field campaigns, we collected 19 fault gouge samples from 15 localities along the PAF, the Labot/Lavanttal Fault, and the Šoštanj Fault. From each locality, we controlled the structures found in the field, which allowed us to relate the observed deformation features in outcrop scale to the activity along each fault.

# New structural data from the Saxonian Granulite Massif: the puzzle of locally overturned metamorphic isograds

Madeline Richter[a], Sebastian Weber[b], Nikolaus Froitzheim[c], Kamil Ustaszewski[a]

[a]Friedrich-Schiller-Universität Jena, Germany, [b]Saxon State Agency for Environment, Agriculture and Geology, Germany, [c]University of Bonn, Germany

The Saxonian Granulite Massif (SGM) hosts the type locality of leucocratic granulites, which are exposed in the core of a SW-NE striking antiform, and which are rimmed by a Lower Paleozoic schist cover. Recently conducted geological and structural mapping in the SGM yielded a new perspective on this major tectonic contact and its immediate associated structures.

Core-associated lithologies are dominantly leucocratic and melanocratic granulites, occasionally garnet-bearing serpentinites, eclogites as well as metagabbros. The schist cover contains mostly metasediments that range from upper greenschist-facies to upper amphibolite-facies conditions from top to bottom. Basal parts of the schist cover constitute garnet-cordierite-sillimanite bearing gneisses, which comprise evidence for migmatisation towards the underlying granulite. Granitoids often decorate this contact. Available P-T-data for grt-crd-sil gneisses and the granulite-facies rocks suggest a characteristic jump in metamorphic peak pressure and temperature (c. 16 kbar and 200-250 °C) between these lithologies. Surprisingly, we found this contact to be overturned on the map scale, with the higher-grade granulites structurally overlying the lower-grade gneisses in some places. Steep as well as flat foliations can be differentiated in the core and cover. Foliations in the hinge of the broad antiform dip shallowly N to NE, whereas flat and steep foliations are found at the NW- and SE-facing limbs. Recumbent folds, involving grt bearing serpentinites, are locally observed in the granulite facies core, and become more abundant in the SE-part of the schist cover. Associated fold axes plunge shallowly N to NE. Stretching lineations and shear-sense criteria show an overall Top SE motion. As migmatisation of the grt-crd-sil gneisses occurred on the prograde metamorphic path during their juxtaposition against isothermally decompressed granulite facies rocks, we suspect a concurrent formation of all observed structures within both schist cover and granulitic core during its exhumation in an overall contractional setting between c. 340 and 330 Ma. Possibly, the presence of granitic melt along the migmatised, basal parts of the schist cover has reduced viscosities. This could have accelerated strain rates in the exhumational shear zone, triggering local folding of the contact between granulites and schist cover.

# Asthenospheric zircon below Galápagos dates plume activity

Yamirka Rojas-Agramonte, Boris J.P. Kaus[a], Andrea Piccolo, Ian S. Willians, Axel Gerdes, Jean Wong, HangXian Xie, Stephan Buhre, Theofilos Toulkeridis, Pilar Montero, Antonio Garcia-Casco

[a]Johannes-Gutenberg-Universität Mainz, Germany

Mantle plumes are active for long periods of time, however dating the onset of their activity is difficult. The magmatic products of the Galápagos plume, for example, have been subducted and fragmentarily accreted to the Caribbean and South American plates. Based on submarine and terrestrial exposures it is inferred that this plume has been operating for $\sim$ 90 Myrs or perhaps even longer (e.g.,$\sim$ 139 Myrs). Here we show that the activity of the plume dates back to $\sim$ 170 Ma. Evidence for this comes from 0 to 164 Ma zircon with a plume isotopic signature (Galápagos Plume Array; GPA) recovered from lavas and sediments from ten islands of the archipelago. Given lithospheric plate motion, this result implies that GPA zircon predating the Galápagos lithosphere (i.e., $>$ 14 Ma) formed at asthenospheric depths (upper mantle $\lesssim$ 50 km). Thermo-mechanical numerical experiments of plume-lithosphere interaction show that old zircon grains can be stored within local stable astenospheric domains to be later captured by subsequent rising plume magmas. These results open new avenues for research on mantle plume dynamics in similar tectonic settings.

## Tectonic modelling of the western Tauern Window in 4D

Julia Beatrice Rudmann[a], David Colin Tanner[a], Michael Stipp[b], Hannah Pomella[c]
[a]Leibniz Institute for Applied Geophysics Hannover, Germany, [b]Martin-Luther-Universität Halle-Wittenberg, Germany, [c]University of Innsbruck, Austria

The western Tauern Window and its surroundings in the European Alps have a high tectonic complexity. Research has been carried out for decades to comprehend the tectonic evolution of this area [e.g., 1, 2]. Nevertheless, not all questions have been solved so far: What is the correct spatial position of the tectonic nappes? How do they continue at depth and above the current topography? Where is the deep Tauern ramp situated and when did deformation chronologically occur?

For better understanding, we aim to tectonically model this part of the Alps using the software MOVE (Petex Ldt.). (1) We will construct and balance tectonometamorphic 2D-cross sections through the westernmost Tauern Window. (2) We will create a 3D-model by implementing other cross-sections (e.g., TRANSALP). (3) We will retrodeform this model in 4D by integrating thermochronological ages (e.g., fission-tracks, OSL, ESR).

This work is principally based on published data, such as geological profiles, maps and ages, but also on our own structural geological fieldwork. Data that was gathered during planning and exploration of the 64-km long Brenner Base tunnel (BBT) offers the unique opportunity to unveil the structural inventory of this part of the Alps. The BBT runs nearly perpendicular to the trend of the Alpine chain through most of its major tectonic basement units [3]. It pierces the western Tauern Window and a number of prominent faults (e.g., the Periadriatic fault system). We will compile geological and geophysical data from boreholes, drill cores, exploration cross-sections and geological maps. Furthermore, we will populate our models with results from microstructural analyses, in particular from elastic anisotropy as well as deformation and metamorphic history. For data preparation, we use ArcMap, MATLAB, Stereonet, and WellCAD software.

In this way, we will quantify the tectonic history of this part of the Alps in as much detail as possible and contribute to the clarification of the subduction evolution of the Alpine Orogeny, in terms of the conceivable reversal in polarity [e.g., 4, 5].

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# Neotectonic activity and fault lineaments in the northern Markgräflerland, Baden-Württemberg, Germany

Julia Rudmann[a], Thomas Kenkmann[b]

[a]Leipniz Institute forApplied Geophysics Hannover, Germany, [b]Universität Freiburg, Germany

The Upper Rhine Graben (URG) represents a synorogenic intracontinental rift system in the Alpine foreland [e.g., 1, 2]. The complex current day fault pattern in the URG area results from the superposition of faults formed during various phases of its crustal stress history [e.g., 2, 3, 4]. Today's stress field is characterized by an approximately NW–SE orientation of the principal stress axis $\sigma 1$ [3] which is responsible for sinistral transtentional conditions in the URG area. In the southern segment of the URG (SW Germany), seismogenic activity [5] indicates that neotectonic processes are ongoing shaping the current day relief. We examined the morphotectonic inventory of the Northern Markgräflerland south of the city of Freiburg utilizing 1 m and 10 m resolution digital elevation models (DEMs) with the program ArcGIS and field work. This area comprises parts of the crystalline basement of the Black Forest, the eastern URG rim fault as well as the terraced URG margin (Vorbergzone). Here we document the following characteristics that are indicative of neotectonic activity: (i) Triangular facets, (ii) terrain steps in alluvial Quaternary river deposits, (iii) shift of tributary creek beds, and (iv) asymmetric hillslope drainage indicative of divide migration.

Triangular facets can be observed along several valley axes in the crystalline basement. They are aligned along both NNE–SSW and WNW-ESE trending valley sides. At the northern entrance of the Münstertal near Staufen they are most remarkable. Here active transtensional normal faulting produced distinct triangular facets in the crystalline basement. The westernmost triangular facet has the maximum size indicating the strongest shoulder uplift.

In Quaternary sediments, we found evidence of neotectonic motion along the URG major fault like Riedel-shear fault patterns, bent and shifted creek beds as well as conspicuous terrain steps in alluvial deposits of the Staufen Bay that run parallel to the URG major fault. The active WNW-ESE trending transtensional fault of the Münstertal also displaces Quaternary deposits. The uplifted crystalline basement adjacent to the URG rim fault is segmented into blocks that are bordered by the aforementioned faults. A northeastward tilting of these basement blocks can be inferred from the fault throw as indicated by the size of triangular facets as well as from the asymmetric hillshapes that show crestlines shifted to the south and larger local catchment sizes on the northern than on the southern hill slopes.

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## Variable fluid flow conditions in fractures identified through the analysis of veins – a case from NE Greenland

Eric Salomon[a], Atle Rotevatn, Thomas Berg Kristensen, Sten-Andreas Grundvåg, Gijs Allard Henstra
[a]Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

We present a case from NE Greenland that exemplifies the use of veins as indicators of past fluid flow conditions in fractures. We analyzed calcite veins that formed in syn-rift clastic sediments in the hanging wall of a major border fault of the East Greenland rift system (Salomon et al., 2020, 2021). Due to fault-controlled fluid flow, a near-fault cementation zone formed quickly after sediment deposition, expressed in pervasive calcite cementation of the deposits. Ongoing deformation was accommodated through fracturing of the cemented rock and fractures were subsequently filled with calcite. All veins trend sub-parallel to each other, are of similar age and, thus, seemingly belong to one fracture set. However, the analysis of these veins reveals three different fluid flow regimes in the fractures:

- No or slow fluid flow: Slow fluid flow conditions are indicated by the minor element concentration of the veins in comparison to the wall rock pore-filling calcite cement. Half of the samples show notable similarities and we interpret that this group of veins formed by diffusion of calcite from the immediate wall rock into the fracture.
- Moderate fluid flow: in another sample group, minor element concentration differs from wall rock cement to vein calcite and we interpret that the solutes were transported through steady fluid advection into the fracture.
- Injected, rapid fluid flow: some veins exhibit multiple extraordinary generations of microcrystalline calcite, which also host wall rock grains.

We argue that this calcite precipitated from a rapidly supersaturated fluid that was injected into the fracture. Outcrops show that the calcite cemented host rock encloses bodies of uncemented porous clastic rock. During continuous burial and increasing burial pressure, these bodies would have been subject to an increase of fluid pressure. Upon fracturing of the surrounding cemented rock, the fluid is injected into the fracture where it is subject to a drop in pressure, which forces quick supersaturation and precipitation.

These results provide remarkable insights to the permeability evolution of fault-bounded reservoir rock that is subject to the formation of a cementation zone. They further highlight how variable hydraulic conditions can be in a fracture network.

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## Arc formation in the Western Alps: consequences regarding the interpretation of geophysically imaged mantle structures

Stefan M. Schmid
Geophysikalisches Institut ETH Zürich, Switzerland

While various authors claimed and still claim slab detachment to have occurred in the Western Alps based on mantle tomography data (e.g. Handy et al. 2021), others (e.g. Malusa et al. (2021) recently proposed that no such slab detachment occurred, seemingly based on the p-wave mantle tomography data of Zhao et al. (2016). However, it can be shown that, contrary to the interpretation of their own data by Malusa et al. (2021), the tomography data by Zhao et al. (2016) clearly indicate that such slab detachment occurred if they are properly analysed in the context of geological data regarding the formation of the arc of the Western Alps. There is in fact no major difference between the tomography data of Zhao et al. (2016) and those of Paffrath al. (2021). This slab detachment allows for SE-directed influx of asthenospheric mantle present below the European plate below Adria. This accommodates the NE-directed roll back of the Apennines. Substantial counterclockwise rotation of western Adria and oroclinal bending is facilitated by a thin orogenic lithosphere (only crust?) present in the southern Western Alps due to slab detachment.

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# Long-lived pulsed intrusions along the Northern Gondwana margin (Central Pyrenees) during the Palaeozoic revealed by LA ICP-MS U-Pb geochronology

Stephan Schnapperelle[a], Jochen E. Mezger[b], Michael Stipp[a], Andreas Gärtner[c], Mandy Hofmann[c], Johannes Zieger[c], Ulf Linnemann[c]

[a]Martin-Luther-Universität Halle-Wittenberg, Germany, [b]University of Alaska, Fairbanks, USA, [c]Senckenberg Naturhistorische Sammlungen Dresden, Germany

Magmatic activity along the northern Gondwana margin, spanning almost the complete Palaeozoic, is recorded in the gneiss domes and plutonites of the Central Pyrenees, part of the western European Variscan orogenic belt. First, there are alkaline granitic dikes that intruded the metasedimentary mantle and orthogneiss cores of the Aston and Hospitalet domes in the Axial Zone of the Pyrenees. These are excellent geochronological archives with their inherited zircon xenocrysts. Beginning with the latest Ediacaran and lasting until the early Permian, felsic magmatic intrusions reflect the Cadomian orogeny in North Gondwana, Ordovician rifting along the northern Gondwana margin with the opening of the Rheic Ocean, and the closure of the Rheic Ocean in the Carboniferous resulting in the Variscan orogenic belt. Second, there are large late-orogenic igneous bodies such as the Bassiès, Marimanha, Riberot and Maladeta plutons. The igneous rocks depict almost the entire Variscan evolution of the Axial Zone. Laser ablation ICP-MS U-Pb zircon geochronology has been applied to dike and pluton samples. Recorded age spectra of detrital, magmatic xenocrystic and inherited zircons reveal a more complex Paleozoic magmatic history of the Variscan basement of the Pyrenees than previously assumed. Inherited and detrital zircons of Mesoarchean to Ediacaran age record the Peri-Gondwana deposition environment of the Cambrian sediments that later formed the metamorphic core of the Variscan Pyrenees. The age spectra of magmatic xenocrystic zircons contain several maxima, such as the middle (475–465 Ma) and late Ordovician (455–445 Ma), early (415–402 Ma) and late Devonian (385–383 Ma), early (356–351 Ma) and middle Carboniferous (ca. 328 Ma). Middle and late Ordovician ages are obtained from dikes that assimilated zircons from the Aston and Hospitalet orthogneisses during their intrusion. The youngest magmatic zircon ages of 306–287 Ma fall into the late Carboniferous and early Permian representing the youngest dike and small granite intrusions. The larger plutons display almost a complete magmatic activity during the Variscan. The main pulses appear at ca. 360-350 Ma, 330 Ma, 320 Ma, 314 Ma and 300 Ma. The youngest magmatic emplacement is observed in the Bassiès pluton at 295 and 285 Ma. Between the different pulses, there is evidence for magmatic reprocessing of the granitoids based on zircon analyses. The presence of early to mid-Carboniferous magmatic zircons in several samples lend further support to a widespread Variscan magmatic activity in the central Pyrenees. The Devonian age peaks cannot be related to any igneous or metaigneous rocks in the central Axial Zone. However, these are thought to be present in the deeper Pyrenean crust, yet to be identified or not yet exposed at the surface. The source of the heat for the Devonian to early-mid Carboniferous magmatic activity remains elusive and may either involve an intracontinental subduction zone or a mantle plume (Tuzo).

# Internal deformation of the Dolomites Indenter, eastern Southern Alps: Insights from a combined field and crustal scale analogue modelling study

Anna-Katharina Sieberer[a], Ernst Willingshofer, Thomas Klotz, Hugo Ortner[a], Hannah Pomella[a]
[a]University of Innsbruck, Austria

Continental indentation is well-documented for the Alps, especially for the indenter's front and sides. Here we focus on indenter-internal deformation within the eastern Southern Alps of Italy and Slovenia. The Dolomites Indenter (DI) represents the northernmost part of the Adriatic microplate and pushes N(NW)-ward into the internal Alps. Using a series of crustal scale analogue models, we aim to link the effect of inherited structures caused by Jurassic E-W extension on the NNW-SSE directed shortening of the DI during Alpine orogeny. This (oblique) basin inversion allows us to test various deformational wavelengths as well as timing and localisation of uplift of the DI's upper to middle crust.

Jurassic NNE-SSW trending normal faults led to a platform-basin-topography (Winterer and Bosellini, 1981) but were inverted during Alpine orogeny. Already in map view changing trends of prominent faults across the DI, e.g. the Valsugana fault system and its transition into the Fella fault, are striking. Changes in fault strikes often seem to be linked with transitions from platforms to basins, as, e.g., in the Cadore area, where the Trento platform merges into the Belluno basin. Pre-existing Mesozoic structures are therefore important for understanding and explaining Paleogene to Neogene crustal deformation within the DI.

The orthogonal to oblique, brittle and brittle-ductile analogue experiments include either (i) pre-scribed strength contrasts between platforms/basins or (ii) graben structures modelled by an initial extensional phase, followed by, in both cases, compression. Modelling results confirm the localisation of deformation in areas of lateral strength contrasts (Brun and Nalpas, 1996), as transitions from platforms to basins represent. Analyses of surface displacement vectors support resulting changes in shortening directions along, due to lateral variations in mechanical strength, curved faults. All models emphasise that the overall style of deformation is less dependent on the material of the basal décollement, but is ruled by the inherited platform/basin configuration, independent of orthogonal or oblique inversion.

To compare analogue modelling results with deformation in the DI, structural fieldwork accompanied by thermochronological sampling was carried out. Examined cross-cutting criteria covering the entire DI comprise evidence for four distinguishable shortening directions: Top SW, Top (S)SE, Top S and Top E(SE). Additionally, shortening directions along several of the studied faults, e.g. the overall SSE-vergent Belluno thrust (Valsugana fault system), change locally from top SSW to top SSE along strike.

Based on what we observe in analogue models, we infer that the variability of shortening directions along these thrust faults may depend on inherited geometries and may not be the result of different deformation phases. One possible conclusion from this observation is that the number of deformation phases in the Southern Alps may have been overestimated so far.

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# Pulverized carbonates and siliciclastic rocks along the Mur-Mürz-fault (Austria)

Sophia Swaton, Kurt Decker
Department of Geology, University of Vienna, Austria

Pulverized rocks are incohesive, in-situ mechanically shattered fault rocks, that can be found worldwide in damage zones adjacent to fault cores. Generally, pulverized rocks are considered to be of seismic origin, and they are characterized by little relative translation and rotation of the fragmented particles. These rocks appear to be macroscopically coherent preserving earlier structures like layering or bedding, but at closer inspection, the rocks are broken down to micrometre scale recording a mosaic-like arrangement of the particles. In this study we investigate pulverized samples are from both carbonate and siliciclastic rocks from the permomesozoic Semmering unit (Lower Austroalpine), close to the Mur-Mürz-fault, a Miocene sinistral strike-slip fault. Samples were selected from drill cores in 500 m depth from the Göstritz site at the Semmering-base tunnel.

The drill core consists of various rock types deformed to different extents but overall appears to be macroscopically coherent. However, the rocks consist of individual fragments that are separated by microfaults, some of which still preserve striations, suggesting at least some component of shear displacement. Siliciclastic material as well as carbonate have been pulverized equally and show the same fragment arrangement. Interestingly, most of the pulverized carbonate rocks record multiple generations of calcite cementation suggesting at least four deformation events but still preserving the mosaic microstructure at the micrometre scale.

In contrast to the strongly cemented fault rocks, directly adjacent pulverized protolith could be investigated in the drill core. It made it possible to study the transition of protolith to highly developed fault rock. Although the exact process of fragmentation is subject of further studies, we speculate that in situ shattering and shaking caused intense brittle fracturing of the rocks, without any further translation and rotation of the individual microfragments.

# Mid-Late Pleistocene fault reactivation in the Tatra Mts: insights from cave deformations and U-Th dating of damaged speleothems

Jacek Szczygieł[a,b], Michał Gradziński[c], Bernhard Grasemann[b], Helena Hercman[d], Wojciech Wróblewski[c], Pavel Bella[e], Juraj Littva[e], Przemysław Sala[c]

[a]Institute of Earth Sciences, University of Silesia, Poland, [b]Department of Geology, University of Vienna, Austria, [c]Institute of Geological Sciences, Jagiellonian University, Kraków, Poland, [d]Institute of Geological Sciences, Polish Academy of Sciences, Warszawa, Poland, [e]State Nature Conservancy of the Slovak Republic, Slovak Caves Administration, Liptovský Mikuláš, Slovakia

The steep and sharp morphology of the Tatra Mountains, together with their highest elevation in the whole Carpathians and clear fault borders, have supported the assumption of tectonic activity of this small but prominent mountain range. Yet, for decades, evidence of this activity has only been provided by indirect indicators, and only recently, the latest Pleistocene $>$ 50 km-long fault rupture along the Sub-Tatra fault was documented. Here, we extend a record of Quaternary deformations of the Tatra Mts. reaching as far as 0.5 Ma, by using U-Th dating of speleothems broken due to cave passage dislocations as a result of the faults reactivation. We recorded cave passages offset with fault-slip data and accompanying ruptured speleothems in six caves. In three other caves, we sampled fallen stalagmites and speleothems to date cave roof collapse to search possible correlations of on-fault and off-fault damage and test the possibility of co-seismic deformation. Some parts of the faults were recorded close to the surface but the biggest offsets (up to 27 cm) were found 200-600 m below the surface, which support their tectonic origin. Although fault-slip data are not uniform and may have been partly affected by the topography, faults were reactivated under an extensional regime with NW-SE extension and $\sigma 1$ plunging steeply to the NE. The dating reveal at least four faulting events: (1) 412 to 332 (-13/+14) ka, which maybe linked with the latest surface uplift phase as inferred from the minimum age of valley bottoms; (2) 280 $\pm$ 7 to 265 $\pm$ 8 ka which coincides with previously documented slope failure initiation; (3) 204.8 (-2.4/+2.5) to 188.8 $\pm$ 1.5 ka; (4) 101.8 (-4.7/+4.8) to 29.3 $\pm$ 1.6 ka; that did not coexist with any previously known deformation.

# Rocks under stress: How dramatic the effect of stress on metamorphic reactions really is?

Lucie Tajcmanova

Ruprecht-Karls-Universität Heidelberg, Germany

Metamorphic reactions within the Earth's interior including deformation and fluid/melt flow are responsible for mountain building, volcanic eruptions and triggering earthquakes. Petrologists and structural geologists are driven by the same essential curiosity about metamorphic processes affecting the Earth's lithosphere and use different tools to understand these processes.

Recent decades have been connected with an impressively accelerating pace in the development and availability of new analytical techniques to earth scientists. Interestingly, the smaller the scale considered, the more heterogeneous an apparently uniform rock sample is. This heterogeneity is not only characterized by variation in chemical composition but also in mechanical properties. The mechanical effects may influence element transport and mineral assemblage in rocks which can, in turn, significantly control the mechanical-chemical coupling rates and mechanisms of various processes in the Earth's interior.

Considering the interplay of metamorphic reaction and mechanical properties in our quantification approaches is critical for correct interpretation of observations in metamorphic rocks. In fact, new theories and quantification approaches have been suggested for systems under stress, mostly based on the observations from deformation experiments focused on the quartz-coesite transition. On one hand, the observation led to interpretations that the maximum principal stress has a major impact on mineral reactions and phase transitions (e.g. Wheeler, 2014). On the other hand, theoretical studies suggested that the heterogeneous nucleation of high-pressure polymorphs is related to the spatially heterogeneous strain or pressure (Ji & Wang 2011; Moulas et al., 2013).

Recently, the combination of deformation experiments together with numerical modelling of rock deformation confirmed the presence of stress and pressure variations during deformation of heterogeneous samples (e.g. Cionoiu et al., 2019). More specifically, the combined numerical models and deformation experiments were performed to quantify the effect of evolving sample geometry on the heterogeneous distribution of mechanical variables such as differential stress and mean stress. Our combined results suggest that the evolving sample geometry is responsible for significant variations in all mechanical parameters that need to be considered in high-stress deformation experiments. Furthermore, the evolution of the locally resolved pressure in time explains the spatial distribution of mineral phases within the sample. Based on these new findings, it is essential to be able to quantify the stress/pressure distribution before any complex thermodynamic interpretations. In fact, any thermodynamic interpretation of a stressed system must take into account the locally-resolved state of stress during sample deformation.

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# Contributions of grain size reduction and shear heating to slab detachment

Marcel Thielmann[a], Stefan M. Schmalholz[b]

[a]Universität Bayreuth, Bayerisches Geoinstitut, Germany, [b]University of Lausanne, Institute of Earth Sciences, Switzerland

In the past, the process of slab detachment has been used to explain different phenomena such as magmatism, rapid topographic uplift and exhumation of metamorphic rocks as well as the occurrence of intermediate-depth earthquakes. Despite its potential importance for all these phenomena, the slab detachment process is still incompletely understood, in particular in relation to ductile weakening mechanisms.

We therefore investigate the impact of different weakening mechanisms on the slab detachment process: structural weakening due to necking, material weakening due to grain size reduction and thermal weakening due to shear heating. We consider a combined flow law of dislocation and diffusion creep. To understand the coupling of these three nonlinear weakening processes, we employ a simple model that describes the evolution of slab thickness, grain size and temperature of a stalled slab. Using these equations, we then determine the material parameters that control the relative importance of the three weakening processes and the two creep mechanisms during slab detachment. Using a combination of analytical and numerical solutions, we then predict detachment times (the time until slab thickness becomes zero) for stalled slabs with different properties.

When both grain and thermal damage are important, grain size reduction and shear heating generate a positive feedback loop resulting in very rapid slab detachment. For Earth-like conditions, we find that the onset of slab detachment is controlled by grain damage and that during later stages of slab detachment thermal weakening becomes increasingly important and can become the dominating weakening process. We therefore argue that both grain and thermal damage are important for slab detachment and that both damage processes could also be important for lithosphere necking during continental rifting leading to break-up and ocean formation.

# Big stories from small crystals: Late Mesozoic to Paleogene unroofing of the Thuringian Forest and its southern periphery (central Germany) from combined zircon and apatite fission-track and U-Pb LA-ICP-MS dating

Manuel Thieme, Fabian Jähne-Klingberg, Bernhard Fügenschuh, Ulf Linnemann[a], Alexander Malz[b], Kamil Ustaszewski[c]

[a]Senckenberg Naturhistorische Sammlungen Dresden, Germany [b]Landesamt für Geologie und Bergwesen Sachsen-Anhalt, Germany [a] Friedrich-Schiller-Universität Jena, Germany

We present new results from a fission track (FT) and U-Pb Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) double dating approach on zircon and apatite from the Thuringian Forest, a prominent fault-bounded basement high in central Germany, and its southwestern periphery with widespread exposures of horizontal Mesozoic strata. Samples were collected from 7 exposures of igneous rocks as well as from Lower Permian (Rotliegend) continental redbeds and volcanics recovered from a borehole southwest of the Thuringian Forest. U-Pb LA-ICP-MS data on zircons from surface exposures of igneous rocks yielded ages between 330 and 300 Ma, confirming emplacement of larger granitoids into late Proterozoic to early Paleozoic, Variscan-deformed country rocks of the Mid-German Crystalline Rise. Apatite FT ages obtained from non-metamict grains range between 86 and 70 Ma, suggesting rock uplift associated with a well-documented and regionally important phase of NNE-SSW-directed intraplate contraction, resulting in spatially homogeneous removal of c. 3 km of late Palaeozoic to Mesozoic rocks. No change in apatite FT ages was detected across the regional-scale Franconian Fault system at the SW-margin of the Thuringian Forest. Additionally, apatite FT ages of the borehole samples southwest of the Thuringian Forest from depths between 963 and 2712 m range from 57 to 18 Ma, suggesting post-Late Cretaceous cooling of this peripheral region. In combination, our data support recent models of a continued large-scale domal uplift of central Germany without verifiable or detectable involvement of individual faults.

# Deformation, reaction and phase mixing in the upper mantle shear zone of northwestern Ronda, Southern Spain.

Sören Tholen, Jolien Linckens

Goethe-Universität Frankfurt am Main, Germany

On the northwestern boundary of the world's largest exposure of subcontinental mantle a major shear zone crops out known as the Ronda shear zone (Andalucia, southern Spain). Showing common characteristics of upper mantle shear zones like an overall decrease in grain size and an increase of (re)crystallized grains towards the shear zone front, ultramylonites are not present. Reaction induced phase mixing has been shown to form ultramylonitic assemblages in other upper mantle shear zones (Lanzo, Erro Tobbio, Othris). By combined crystallographic and geochemical analysis on microstructures from varying distance to the shear zone front (range: 39 to 703 m), this study investigates the extent and origin of phase mixing in the Ronda shear zone and its impact on strain localization.

Beside olivine as major phase, pyroxenes and spinel were found as interstitial or film-like grains throughout the matrix, independent of the proximity to the shear zone. A strong, common crystallographic preferred orientation of olivine (CPO) in the matrix suggests that most deformation was accommodated by olivine. Nevertheless, approaching the shear zone front pyroxene porphyroclasts show increasingly polyphase neoblast tails. In these tails the olivine CPOs diminish and are indicative for the presence of fluids. Mixed matrix and porphyroclast tail microstructures revealed a stepwise process of mixing in the shear zone. The first step is represented by the interstitial and mostly internal deformation-free pyroxenes and spinels found independent on the distance to the shear zone front. Their small grain size, irregular or film-like shape and their sinuous, xenomorph grain boundaries point to a crystallization from interstitial Si-rich melts. The melt originates within the deeper part of the peridotite complex due to a thermal event after thinning of the subcontinental lithosphere (Soustelle et al., 2009). The second step is evidenced by an increasing amount of pyroxene porphyroclast reaction tails towards the shear zone front. In these microstructures, pyroxene porphyroclasts form a tail of pyroxene, amphibole, olivine ± spinel neoblasts. Neoblasts are present at porphyroclast grain boundaries and partly indent in the parent clast. The presence of amphibole in these tails and their increasing occurrence towards the shear zone front indicates a fluid infiltration from the shear zone front.

Both aforementioned processes and their associated microstructures point to a reaction induced phase mixing rather than a mechanical mixing. Even though reactions formed the polymineralic, fine-grained tails, the strain was not localized there, and no ultramylonite bands were formed. The absence of strain localization in these tails is likely due to the lack of switch from dislocation creep to diffusion creep. Together with the presence of an overall strong olivine CPO it indicates a broad distribution of deformation in the entire shear zone which was accommodated by dislocation creep.

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# Andalusite-bearing pseudotachylytes: a new pressure constraint for the northern hanging wall of the Woodroffe Thrust (Musgrave Ranges, central Australia)

Giovanni Toffol[a], Giorgio Pennacchioni[a], Alfredo Camacho[b], Neil Mancktelow[c]

[a]University of Padova, Department of Geosciences, Padova, Italy, [b]University of Manitoba, Department of Geological Sciences, Winnipeg, Canada, [c]ETH Zurich, Department of Earth Sciences, Zurich, Switzerland

A relevant source of information on middle and lower crustal seismicity is provided by exhumed deep-seated pseudotachylytes (pst: quenched coseismic frictional melts). A pre-requisite of any process-oriented study of these pst is the precise estimate of ambient pressure and temperature during faulting. Here we use the mineralogy and microstructures of pst within peraluminous granulite-facies gneisses from a north-eastern section (25°59'32"S 132°08'36"E) of the hanging wall of the Woodroffe Thrust (WT, Musgrave Ranges, central Australia) to constrain the depth of seismic faulting. The WT is a south dipping mylonitic zone developed during the Petermann orogeny (630-520 My) and it hosts, in the hanging wall, the largest volume of supposedly deep-seated tectonic pst in the world. It has previously been described, with some uncertainties for the northern sections, as a shallowly-dipping (6°) structure with pressure, at the time of earthquake faulting, ranging from 1.0 – 1.3 GPa (south) to 0.8 – 1.1 GPa (north) along a ca. 60 km of N-S exposure in the transport direction[1].

The host rock of pst shows a mm-thick alternation of quartz-feldspar and cordierite-sillimanite-rich layers. Close to pst the host rock is intensely fractured. Along fractures, cordierite is replaced by a symplectite of quartz, andalusite and biotite associated with magnetite and acicular kyanite. Kyanite also overgrows biotite statically. Contrary, sillimanite does not react even where shattered. The pst contains microlites of andalusite, sillimanite and kyanite together as well as cauliflower garnet. The globular andalusite microlites, commonly surrounding a quartz clast, form symplectite-type intergrowths with vermicular quartz and are pseudomorphosed by biotite at the rims. Andalusite globules are single crystals and adjacent globules commonly share the same crystallographic orientation. The vermicular quartz in andalusite also show a crystallographic preferred orientation identical to that of the quartz clast core. Prismatic to acicular kyanite microlites locally overprint altered andalusite aggregates, or epitaxially overgrow former clasts of kyanite. Prismatic sillimanite microlites epitaxially overgrow on opposite sides of sillimanite clasts. Dendritic (cauliflower type) garnet is the last microlitic phase to crystallize and commonly includes magnetite and locally kyanite. Along the fault veins, the globular poikilitic andalusite is dismantled to disorganized aggregates of andalusite and quartz and kyanite needles are aligned along the foliation developed at a low angle to the pst boundary. All microstructural observations indicate that faulting occurred at conditions within the stability field of andalusite + kyanite, with the growth of sillimanite microlites only promoted by the transient thermal pulse. This implies pressure equal or below 0.5 GPa, i.e. shallower conditions than previously inferred. Our new observation suggests a more complex geometry of the WT than a simple, shallowly dipping plane.

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# Structural Geology in the Site-selection of the Swiss Repository for Radioactive Waste

Tim Vietor

Nagra Safety, Geology and Radioactive Materials, Switzerland

The site selection process for the deep geological repositories in Switzerland is in its final phase. Using surface-based exploration methods, including 3D-seismics and deep boreholes, Nagra has recently collected the necessary data to select the most suitable site.

The sites will be compared based on 13 technical criteria defined in 2008 and already used in the two previous phases of the selection process. The criteria comprise safety-related aspects including the barrier properties and their long-term stability, as well as the construction suitability of the repository and its access facilities.

In our contribution we present the stepwise approach for the exploration within the site selection process. We show how we integrate third party data, seismic surveys, surface mapping as well as deep and shallow boreholes to build purposed models. These models serve to sharpen and test our understanding of the observational data and to calibrate predictive models with the past evolution. Such models will then be used to develop scenarios of the future geological and hydrogeological evolution of the different sites. Fundamental for such modelling is a sound understanding of the recent geological past including the role of faults as fluid conduits or barriers. In order to decipher regional fluid pathways we integrate geochemical fingerprinting of deep and shallow aquifers, tracer profiles in clay-rich formations and dating of deformation structures wherever possible.

Example data sets from the ongoing deep drilling campaign and recent 3D seismic surveys will be used to illustrate our approach to distinguish the remaining sites according to long-term safety and to underline the large safety margin of the selected clay host rock in long-term evolution scenarios.

# Metamorphic origin of the Cassiterite Mineralization in highly-mature paraseries of the Garnet-Phyllite Unit, Western Erzgebirge, Germany

Sebastian Weber[a], Claus Legler, Enrico Kallmeier, Bernhard Schulz, Mathias Burisch
[a]Saxon State Agency for Environment, Agriculture and Geology, Germany

The Erzgebirge hosts numerous stratiform tin occurrences, which are located along the same structural level within the Variscan orogenic belt. One of these tin deposits, the Bockau tin occurrence, is located in the area between Aue-Bad Schlema – Bockau – Zschorlau with alternating sequences of quartzite and metaschist. This banded sequence records geochemical signatures of intensely weathered sedimentary rocks. Their protolith probably formed during the Ordovician at the passive continental margin of Gondwana. The mineral assemblage consists of quartz + biotite + garnet + muscovite + andalusite + chlorite + cassiterite + accessory-phases. All silicate minerals are clearly of metamorphic origin. While quartz and biotite are the most abundant among all phases, subordinate amounts of garnet and andalusite form single isolated porphyroblasts. Muscovite and chlorite appear as retrograde phases. Cassiterite grains are concentrated in layers concordant to the foliation plane, occur as inclusions within foliation parallel Fe-biotite/Siderophyllite, and are overgrown by garnet blasts. This texture indicates that cassiterite has been present prior to the Variscan continental collision. The frequent occurrence of cassiterite also correlates with the high Sn-contents of the tin deposit (ranging from $< 50$ to 5000 ppm). Different methods of conventional thermobarometry and pseudosection modelling were applied to reconstruct the regional metamorphic overprint at $550 \pm 50$ °C / $9 \pm 1$ kbar and a subsequent thermal peak of $> 600$ °C. These results are characteristic for the metamorphic conditions reached in the Garnet-Phyllite Unit, though the maximum temperatures reached are slightly higher than previously thought. There is a lack of evidence for a post-magmatic / metasomatic history of the Bockau tin occurrence by the applied methods and petrographic observations.

# The fault network of northern Bavaria, Germany – a (pseudo) 3D approach

Johannes Wiest, Daniel Köhn, Harald Stollhofen

FAU Universität Erlangen Nürnberg, GeoZentrum Nordbayern, Germany

Faults are not only essential elements of geologic histories, but also have a large significance for many societal topics today, such as geothermal energy, carbon capture and storage or nuclear waste disposal. In the area of the Permo-Mesozoic Franconian platform in northern Bavaria (Germany) the existence, geometries, kinematics, and properties of fault zones are poorly constrained or virtually unknown due to limited exposure and lack of geophysical data coverage.

To address this issue, we have constructed an internally consistent network of 18 geological cross sections with 68 intersections covering northern Bavaria. Data input is provided by $> 3500$ wells and high-resolution geological maps and complemented by geophysical surveys and field data. In this presentation, we introduce the workflow of profile construction, which is enabled by the qProf plugin for QGIS. We then show how the cross-section network can be used to determine the location and geometries of fault segments, resulting successively in the construction of an entire fault network.

While we highlight the non-uniqueness of our interpretation, we demonstrate that this pseudo-3D approach is critically testing the plausibility of existing maps. Furthermore, it allows to incorporate basic measures of uncertainty and scale-dependency in the resulting model. We emphasize that this is an important step forward from previously available datasets.

## Fault scaling on Memnonia Fossae, Mars: Displacement-length relationship derived from the HRSC data

Isik Su Yazici, Ernst Hauber
DLR-Institut für Planetenforschung, Berlin, Germany

Geometric fault properties can provide insights into the mechanical and temporal evolution of fault systems [1,2], and the past and future potential for seismic energy release [3]. Since the seismic moment released during the growth of a fault is strongly connected to the fault geometry, the study of fault populations can also help to estimate the current seismicity level [4,5]. Until today, only few data on the relationships between fault displacement and length have been collected for extraterrestrial bodies [6], partly due to the limited number of reliable topographic datasets.

The InSight mission put a lander in the Elysium region of Mars in 2018. It is equipped with a seismometer [7] that has recorded several marsquakes for which the locations could be determined [8]. As a starting point for our analysis of fault geometries, we selected the Memnonia Fossae fracture systems, one of the hypothesized locations for marsquakes, which radiate outward from the Tharsis region in a southwesterly direction.

Here we use DEM and orthoimages from HRSC [9] to obtain information on the displacement distribution along fault traces. This also enabled determining the maximum displacement. We compare our results to previous measurements of faults on Mars, Earth, and beyond. Based on these analyses, we discuss the implications of fault segmentation and linkage for further interpretation. HRSC data offer high-resolution topography and spatially contiguous coverage, which are required to analyze detailed topographic characteristics of large fault systems. For structural interpretation of key locations (e.g., relay ramps), CTX images ($\sim 5 - 6$ m px-1) have been inspected. Fault length was digitized along the fault line, and multiple topographic cross-sections across the fault were drawn with a spacing of $\sim 1$ km. Fault throw (a proxy for true displacement) was visually determined in the digitized cross-sections. At the time of writing, 16 images out of 75 available images/DEM from the Memnonia Fossae region exhibiting normal faults have been measured. We find an average Dmax/L ratio of 0.007, consistent with our previous findings for other regions on Mars, where this ratio had an average value of 0.006 [10]. At the conference, we will present further measurements and discuss them in the context of the regional structural geology.

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