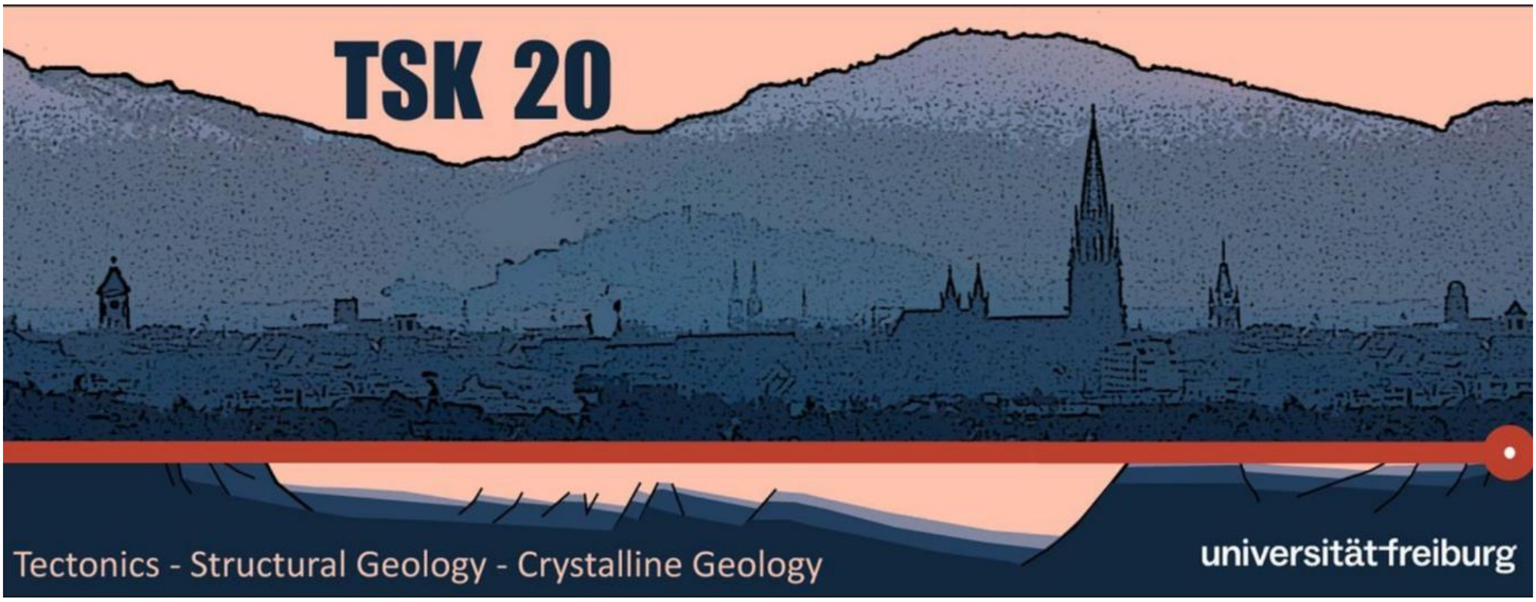

TSK 20 Freiburg **17.-22.03.2024**

20th Symposium

Tectonics, Structural Geology and Geology of Crystalline Rocks

20. Symposium

Tektonik, Strukturgeologie und Kristallingeologie

TSK 20 Freiburg **17.-22.03.2024**

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TSK20 Programme Freiburg

Monday, 18.03.2024

09:00 – 9:15 Opening Ceremony			
09:15 - 12:05 Oral sessions			
	Session chairs: Kley, Riller		
	Mountain Building Processes & Alpine Tectonics		
Keynote	**09:15**	**Handy**	**A fresh look at mountain-building from the Alpine perspective**
	09:55	Pomella	The Alpine cooling history of the eastern Southern Alps
	10:15	Sieberer	Exploring the impact of inherited structures on deformation and uplift in fold and thrust belts through multi-scale analogue modelling: a case study in the European eastern Southern Alps
10:35 - 11:05 Coffee break			
	11:05	Rudmann	Restoring the nappes of the western Tauern Window using thermochronological and petrological constraints
	11:25	Weber	Reprocessing of the NRP 20 traverse E1 in eastern Switzerland
	11:45	Kroner	Initial Collision of Gondwana Promontories with Forming Laurasia - The Orogenic Record of Western Pangea in the Devonian
12:05 - 13:05 Lunch break (Mensa)			
	Session chairs: Grasemann, Tanner		
13:05 - 17:35 Oral sessions			
	Geodynamics & Plate Tectonics		
Keynote	**13:05**	**Behr**	**The influence of sediments on subduction dynamics.**
	13:45	Kaus	Gibraltar subduction zone is invading the Atlantic
	14:05	Hildebrand	Large-scale anatomy of a deep subduction megathrust: observations from the Cycladic Blueschist Unit on Syros, Greece
	14:25	Matthies	Insights into the deformation pattern and the edifice stability of oceanic volcanoes from direct shear experiments and finite-element models: A case-study of Anak Krakatau (Sunda Strait, Indonesia)
	14:45	Nagel	Variations of Earth's volume driven by intermittend mantle stratification
15:05 - 15:35 Coffee break			
	Session Chairs: Ustazewski/Hauber		
	Applied Structural Geology		
Keynote	**15:35**	**Schmatz**	**Salt rock mechanics in the natural laboratory**
	16:15	Svensson	Microstructural evolution of a 40 year old crushed salt backfill - Quantitative microstructural analysis
	16:35	Schäfer	Fault rocks and the energy transition: from oil and gas to carbon dioxide storage
	16:55	Abe	The “Restless”-Project: Investigating the impact of lithology on the risk of induced seismicity in deep geothermal reservoirs
	17:15	Hallas	Geochemical Classification of Thuringian Granites using Multi-Dimensional Scaling
	17:35	Scheck-Wenderoth	Deep thermal field in plate tectonics
19:00 - 20:00			
Public talk	**Oncken**		Forschung für eine Erde im Wandel – von Erdbeben, schwarzen Schwänen und planetarer Bewohnbarkeit.

Tuesday, 19.03.2024

09:00 - 12:10 Oral sessions			
	Session chairs: Pomella, Stipp		
	Experimental Rock Mechanics, Seismo-Tectonics		
Keynote	**09:00**	**Dresen**	**Precursory Deformation and Earthquake Nucleation – Laboratory Results**
	09:40	Nevskaya	Implications for the strength of the Earth's middle crust from novel experiments on natural fine-grained granitoid rocks
	10:00	Muldashev	Modeling of earthquakes in extensional tectonics
	10:20	Tajcmanova	Experimental investigation of serpentinite dehydration induced by earthquake-like pressure drops
10:40 - 11:10 Coffee break			
	11:10	Zhan	The Frictional-Viscous Transition in Experimentally Deformed Granitoid Fault Gouge
	11:30	Fusseis	Transformative insights into reacting, deforming rocks through operando xray imaging experiments - elastic stress control on fabric formation and fluid transport properties
	11:50	Peacock	Fracture corridors in crystalline rock and implications for geothermal resources
12:10 - 13:10 Lunch break (Mensa)			
13:10 - 16:40 Oral sessions			
	Session chairs: Kaus, Reicherter		
	Microstructures, Deformation Mechanisms & Rheology		
Keynote	**13:10**	**Di Toro**	**Fault processes and shock deformation during earthquakes.**
	13:50	Trepmann	Quartz cleavage fracturing and subsequent recrystallization along the damage zone recording fast stress unloading
	14:10	Poelchau	Shear stresses in experimentally shock-twinned calcite
	14:30	Müller	The crystallographic preferred orientations and structural anisotropies of felsic plutonites – First results of a comprehensive study of German granites
14:50 - 15:20 Coffee break			
	15:20	Kilian	On the control of quartz crystallographic preferred orientation development
	15:40	Nowak	Metamorphic record preserved in ultrahigh-pressure eclogites (Śnieżnik Massif, NE Bohemian Massif)
	16:00	Toffol	On-fault earthquake energy density partitioning recorded in seismically shocked garnet.
	16:20	Kley	New ideas from old observations: An example from the Leinetal graben
16:40 - 21:00 Poster session			

Wednesday, 20.03.2024

09:00 - 12:30 Oral sessions			
	Session chair: Trepmann, Fusseis		
	Planetary Tectonics & Impact Cratering		
Keynote	**09:00**	**Rae**	**Dynamic strength, fragmentation, and the impact cratering process.**
	09:40	Eisermann	Testing different mechanisms of long-term crustal modification of large impact craters inferred from scaled analogue experiments
	10:00	Riller	Possible causes for the formation of sinkholes in post-impact strata of the Chicxulub crater, Yucatán Peninsula, Mexico
	10:20	Kenkmann	Structure of the marine target impact crater nadir inferred from 3D-seismics
10:40 - 11:10 Coffee break			
	11:10	Hauber	Neotectonic movements in Claritas Rupes region on Mars
	11:30	Karagoz	Tectonic history of the Tharsis Rise on Mars inferred from wrinkle ridges: multi-stage plume activation and critical taper dome
	11:50	Carboni	3D structural analysis of symmetric, asymmetric, and doubleridges wrinkle ridges on Mars
	12:10	Yazici	Fault scaling on the Reykjanes Peninsula (Iceland) as a Mars Analogue: Displacement-length relationship in comparison with Memnonia Fossae, Mars
12:30 - 13:30 Lunch break (Mensa)			
13:30 - 17:20 Oral sessions			
	Session chair: Herwegh, Handy		
	Neo-Tectonics & Tectonic Geomorphology		
Keynote	**13:30**	**Wolf**	**Quantifying the interaction between surface processes and tectonics during mountain building: the Beaumont number.**
	14:10	Hergarten	Theoretical and numerical considerations of faceted topographies at normal faults
	14:30	Reicherter	Paleoseismic studies of the estern Rhine Graben Faults (Germany)
	14:50	Pena-Castellnou	Fault segmentation along the eastern margin of the Upper Rhine Graben by tectonic geomorphology
	15:10	Stemberk	The nowadays stress field changes recorded by 3-D extensometers TM-71 within the Upper Rhine Graben
15:30 - 16:00 Coffee break			
	16:00	Mair	Multi-Geophysical Imaging of Neotectonic Faults in the Northern Upper Rhine Graben
	16:20	Hürtgen	The Paleoseismic Database of Germany and Adjacent Regions PalSeisDB v2.0 - updated and extended
	16:40	Brandes	Deep crustal earthquakes in northern Germany
	17:00	Ferreira	Usage of UAV-based photogrammetry for quantifying the kinematics if first-order faults
17:20 Quo vadis TSK			
19:30 - 22:00 Conference Dinner			
Restaurant Dattler Schlossberg, Am Schlossberg 1, 79104 Freiburg			

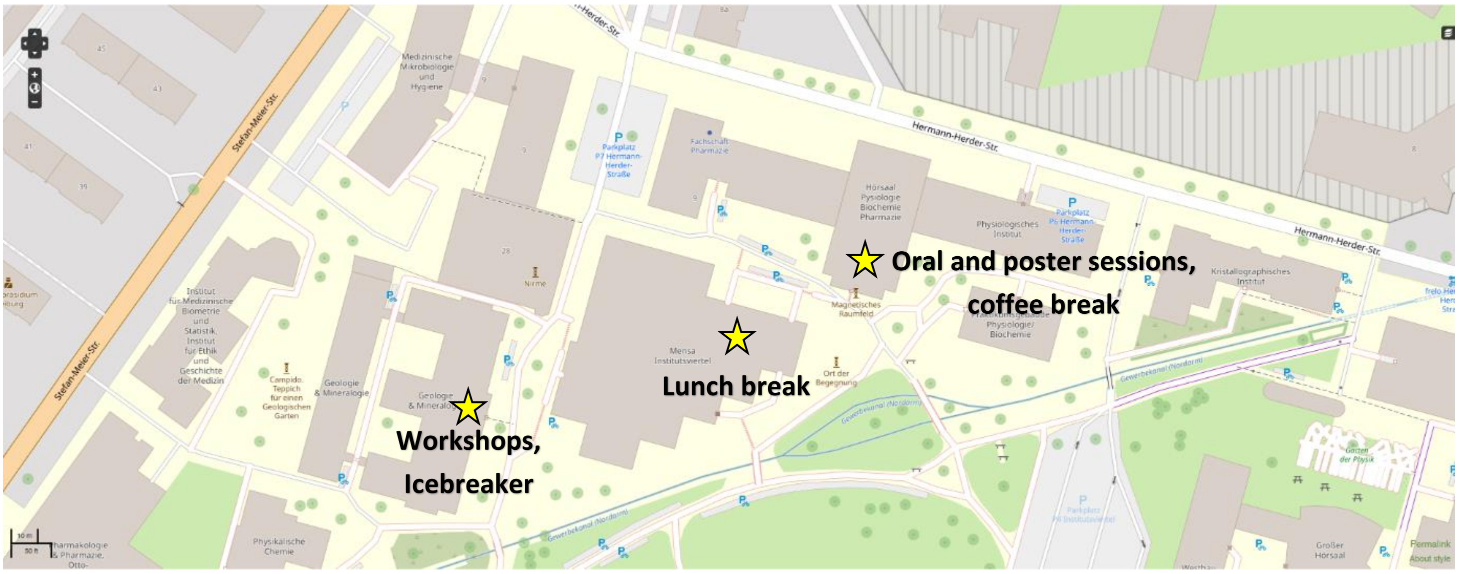
TSK20 Posters

Neo-Tectonics & Tectonic Geomorphology		
101	Kanzler	Neotectonic deformation of Pleistocene sedimentary deposits in the Lardos Basin, Rhodes Island, Greece, points to tightening of the Hellenic arc
109	Doski	Active Faults in Kurdistan, Northern Iraq
113	Szuba	Basin formation caused by plate boundary-parallel extension, Island of Rhodes, Greece
115	Grolms	Variation of principial strain axis directions with proximity to first-order fault zones and its importance for elucidating forearc deformation on the Island of Rhodes, Greece
127	Steinritz	Preliminary results of paleoseismological trenching along the Feldbiss Fault (Lower Rhine Graben, Germany)
144	Zebari	Topography of the southwestern margins of the Bohemian Massif (Bavarian Forest): the role of Late Cenozoic tectonics
146	Lefevre	Relation between fault activity and scarp morphology in the Lower Rhine Graben
155	Hürtgen	Geological-Geophysical and Sedimentological Analysis of Soil Liquefaction Phenomena along the Kupa River caused by the December 29 Earthquake in 2020, Petrinja (Croatia)
Modelling Deformation from the Micro- to the Mega-Scale, Geodynamics & Plate Tectonics		
126	Tanner	Restoration and improvement of cross-sections of the Osning Fault System in northern Germany
Applied Structural Geology		
116	Degen	Geologist’s Compass TJD
Planetary Tectonics & Impact Cratering		
122	Sturm	Comprehensive structural and petrographic analyses of drill core samples from the center and rim of the small (60 x 41 m) impact crater SM-1 of the Wyoming crater field, USA
123	Sturm	Structural analysis of the recently discovered deeply buried complex Jake Seller Draw impact structure in the Bighorn Basin, Wyoming, USA
143	Kitha	Deformation microstructures related to low-angle normal faults of the Rochechouart impact structure, France
General Tectonics & Regional Studies, Metamorphism & Deformation		
124	Keseberg	Petrological diversity of ultra-high-pressure rocks around the Saidenbach dam (Erzgebirge)
125	Möckel	Regional and structural geology of Neoproterozoic to Lower Cambrian rocks in the Ouansimi copper mine, Western Anti-Atlas of Morocco
136	Schulze	The juxtaposition of the Lausitz and the Erzgebirge during the variscan orogeny – a tectonic case study of the Elbtalschiefergebirge, Elbe zone
140	Silva	First constraints and geodynamic implicactions of cryogenian metamorphism in the foreland orogenic basement of the southern Dom Feliciano Belt (Uruguay)
175	Berckhan	Reconstructing the emplacement conditions of the Bažina Maar (CZ) volcanic rocks by investigating the in- and out-of-phase anisotropy of magnetic susceptibility
176	Eickhoff	Seismic reprocessing and imaging visualize detachment depths and backthrust reflections within the Variscan Eifel Fold-Thrust Belt, Germany

TSK20 Posters

Metamorphism & Deformation, Geodynamics & Plate Tectonics		
121	Awoum	Metamorphic history and geodynamic significance of the MORB-derived amphibolites from the Bankim area in the Foumban-Bankim Shear Zone: evidence of subduction, late Paleoproterozoic
Microstructures, Deformation Mechanisms & Rheology OR Metamorphism & Deformation		
102	Koenemann	Shear dilation, a new thermodynamic state function: physics of earthquakes in the crust and at 600 km depth
107	Bestmann	Seismic induced anisotropy and kinking in quartz
117	Achu	Kinematic evolution of the Ngwi area along the Pan-African Central Cameroon Shear Zone (Adamawa-Yadé domain): Implications for emplacement of the Ngwi granitic pluton
133	Hill	Resolving Eo-Alpine kinematics of the Plattengneis Shear Zone (Koralpe, SE Austria) via EBSD & crystalline vorticity axis analyses.
134	Lang	A realistic upper bound of elastic anisotropies in schists and phyllites at the NW margin of the Tauern Window (Eastern Alps, Austria)
150	Kühn	Tectonic modification of clay mineral alignment in sediments from the Hikurangi accretionary prism (NZ)
152	Pfeifer	The influence of different clast types on clay mineral alignment in Opalinus clay – first results
156	Kilian	On the control of quartz crystallographic preferred orientation development
162	Wilke	The nature of NW-directed shearing at the bottom of the nappe pile in the Erzgebirge
Mountain Building Processes & Alpine Tectonics		
139	Klaus	Sliding processes versus thrusting: Lechquellengebirge, Vorarlberg, Austria
141	Sieberer	Relationships between sizes of inherited basins and fold-and-thrust belts in crustal-scale analogue models: evolution of the European eastern Southern Alps
154	Muldashev	Architecture of Subducted Rifted Continental Margin and Dynamics of Early Collision
159	Fuhrmann	Deformation at the base of the Bergell Pluton in the upper Valle dei Ratti (Italy)
166	Bülhoff	Pseudotachylites along the Pustertal-Gailtal-Line, eastern Periadriatic Fault system, Austria
172	Thieme	Late Mesozoic to Palaeogene cooling history of the Thuringian Forest basement high and its southern periphery (Central Germany) revealed by fission-track dating
180	Walde	The Geology of the Suldtal area, with focus on the Stratigraphy and Detrital Geochronology of the Flysch units

TSK20 Conference venue locations



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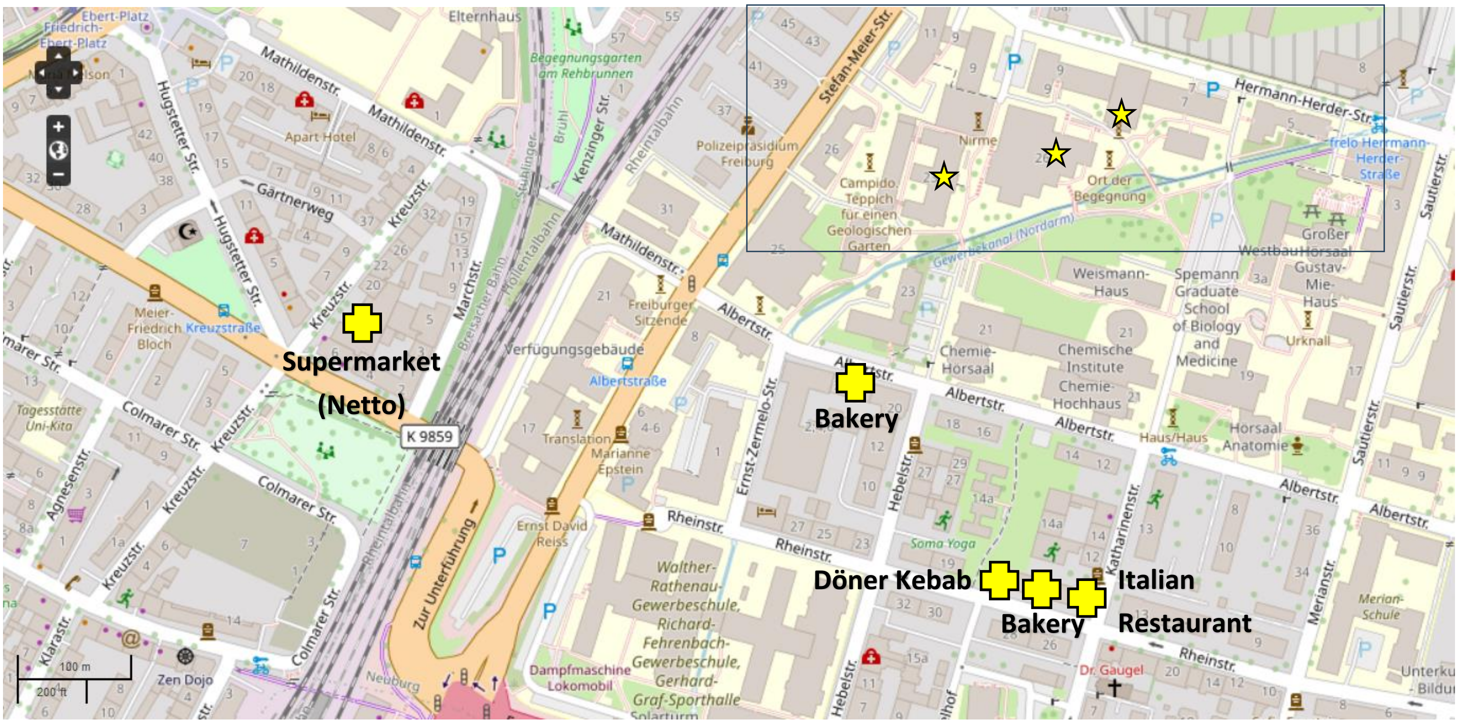

Abstracts

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20. Symposium

Tektonik, Strukturgeologie und Kristallingeologie

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DGGV Deutsche Geologische Gesellschaft Geologische Vereinigung

ID: 100
Abstract Submissions
Topics: Planetary Tectonics & Impact Cratering

Possible causes for the formation of sinkholes in post-impact strata of the Chicxulub crater, Yucatán Peninsula, Mexico

Ulrich Riller, Jan Oliver Eisermann, Louisa Kanzler

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The 66 Ma Chicxulub impact crater, Yucatán Peninsula, Mexico, is obscured by hundreds of meters thick horizontal carbonate strata, which at surface are as young as Pliocene. The spatial density of karst-induced sinkholes, known as cenotes, is maximal at, and aligns with, the southern portion of the buried crater margin, forming a distinct semicircle, about 170 km in diameter. The causal relationship between the presence of the buried crater margin and the formation of the partial cenote ring has remained elusive since the discovery of the Chicxulub crater, by now some 30 years ago. Earlier hypotheses, by which the cenotes formed due to subsurface collapse of either impact breccia or porous reef complexes lined with the crater margin have received little support. However, it is well known that ground water flow of the northwestern Yucatán aquifer is channelled in post-impact carbonate rock below the cenote ring. This calls for the presence of prominent structural discontinuities in carbonate strata above the buried crater margin.

We addressed cenote formation in the realm of the Chicxulub crater by scaled analogue experiments and by remapping the locations and surface outlines of some 6500 cenotes using imagery embedded in ArcGISPro. The outlines are mostly elongate, suggesting that cenotes formed by preferential dissolution of carbonate rock at planar structural discontinuities. This interpretation is corroborated by the overall shape-preferred orientation of their outline long axes in E-W direction, throughout the northern portion of the Yucatán peninsula. Interestingly, long axes deviate from this trend for many of the cenotes defining the partial ring. Such directional departure points to local perturbation of deformation, and thus stresses, preceding cenote formation above the crater margin. Physical experiments using photo-elastic materials as analogues for continental crust are currently designed to explore to what extent far-field maximum compressive stresses, imparted by plate convergence at the Middle-America Trench, may account for the perturbations in carbonate rock above the crater margin.

Long-term isostatic relaxation of crust below large impact craters is an alternative hypothesis for the formation of concentric faults, potentially localizing at crater margins and thus, generating the partial cenote ring. Using two-layer analogue experiments scaled to the physical conditions on Earth and modelling the deformational behaviour of lower and upper crust following crater formation, we explored the structural and kinematic consequences of crustal relaxation by systematically varying initial depths and diameters of crater floors. Model results indicate that Chicxulub-size craters do indeed develop concentric faults at crater margins by accomplishing differential displacement between uplifting crater floors and subsiding peripheral areas. Interestingly, crater floors retained structural coherence during uplift, which aligns with the paucity of cenotes within the respective ring at Chicxulub. Based on our scaling of experiments, the duration of isostatic relaxation translates to natural time scales of at least tens of thousands of years. Although isostatic relaxation of impacted crust may not solely account for the origin of a structurally controlled cenote ring at Chicxulub, concentric faults generated by this mechanism may propagate with time through post-impact strata, driven by far-field stresses.

ID: 101
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Neotectonic deformation of Pleistocene sedimentary deposits in the Lardos Basin, Rhodes Island, Greece, points to tightening of the Hellenic arc

Louisa Kanzler, Malu M. M. Ferreira, Ulrich Riller

Universität Hamburg, Germany; louisa.kanzler@outlook.de

The Island of Rhodes is part of the eastern forearc segment of the curved Hellenic subduction zone. Based on micropaleontological evidence, crust forming the island underwent several uplift-subsidence cycles during the Pleistocene. Yet, structural evidence for these tectonic motions is not well known but is paramount for identifying the overarching geodynamic regime that affected the Hellenic plate boundary. Regimes that are discussed include subduction roll-back, tightening of the Hellenic arc, gravitational spreading of the Aegean upper plate, and rotation of the Anatolian Block. Analyzing neotectonic deformation of forearc rocks is a way forward to discriminating among these processes. Thus, we documented evidence for neotectonic movements by focusing a structural analysis on Pleistocene sedimentary rocks of the Lardos Basin, located on the SE-coast of Rhodes Island. These deposits are made up of fossiliferous carbonate and clay-rich sedimentary strata of the 0.8 – 0.4 Ma Cape Arkhangelos and Lindos Bay Formations.

Evidence for post-Pleistocene deformation is based on remote sensing of geomorphological lineaments using SRTM data as well as field-based structural analyses employing differential GPS and UAV imagery. While the sedimentary strata of the Cape Arkhangelos and Lindos Bay Formations are mostly subhorizontal, the contact between the two formations is displaced by a set of first-order, NW-striking normal faults. Additionally, some 40 higher-order NW-striking shear faults, primarily normal faults, were documented within a distance of a few hundred meters to the master faults in both formations. The strike of these faults matches the trend of a prominent lineament set within and around the Lardos Basin. Collectively, the normal faults and lineaments indicate post-Pliocene NW-SE extension, which is also known from other areas of the eastern Hellenic forearc. Thus, this extension direction seems to be a hall mark of this forearc segment, amounting to plate boundary-parallel extension. In summary, the kinematics of neotectonic deformation on the SE coast of Rhodes points to longitudinal stretching of forearc rocks and is compatible with tightening of the Hellenic arc.

ID: 102
Abstract Submissions
Topics: Metamorphism & Deformation

Shear dilation, a new thermodynamic state function: physics of earthquakes in the crust and at 600 km depth

Falk H. Koenemann

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The mechanics of solids theory is pre-modern. It is successful for elastic deformation under pure and axial shear, but fails for other deformation types. Especially the physics of fracture remains enigmatic, including earthquakes in the Earth's crust and in the mantle at 600 km depth in some subduction zones. The Euler-Cauchy theory originated in the 18th C. However, the conceptual tools of physics and mathematics to properly understand the nature of solids and fluids subjected to anisotropic loading did not exist before 1840, and were fully available only from 1870 on. *Elastic deformation is by nature a change of state in the sense of the First Law.* This cannot be concluded from the Euler-Cauchy theory which, among other flaws, is ignorant both of the First Law, and the concept of physical work; work done by shear forces cannot even be defined [1, 2].

A thermodynamic approach to elasticity offers better insight [3]. Anisotropic loading is decomposed for mathematical reasons into four parts. (1) The average loading is isotropic, causing a volume contraction. The deviatoric field consists of (2) the normal-forces-only component the effect of which is neutral, and (3+4) the shear-forces-only component which counts twice. The work done by shear forces amounts to a new thermodynamic state function that can occur only in anisotropic loading. It always results in a volume expansion, hence it is called *shear dilation*. In pure shear its effect is hidden since it balances with component (1); in simple shear the expansion is larger than component (1), the effect is measurable and observed experimentally (Poynting 1909). This effect is the cause of earthquakes.

Shallow quakes: The region around a large strike slip fault is therefore elastic-reversibly expanded. This has two effects. (A) Since the crust is confined laterally, the only direction permitting dilation is upward. That uplift (mm to cm) can be measured by satellite telemetry. (B) Since horizontal expansion is impossible due to regional constraints, loading causes the fault to become progressively locked. This way, the crust is able to store an immense elastic potential over a large rock volume sufficient for Mag 7 quakes.

Deep quakes: Some subduction slabs (Tonga, Colombia) produce quakes at >600 km. Their origin is completely enigmatic since at T ~ 1000°C yielding should be plastic. However, they occur just above the 660 km discontinuity where the material density increases by 40%. Therefore the slab is unable to penetrate the lower mantle; it hits an obstacle. Therefore it is anisotropically loaded. The resulting shear dilation is small in absolute numbers, but large relative to the material's internal pressure. Deep and shallow quakes therefore have precisely the same origin: the elastic shear dilation causes the material to fail. The Euler-Cauchy theory is unable to offer such insights.

[1] Int J Modern Physics B **22**, 4863-4876 (2008); [2] Eur J Physics **35**, 015010 (2014); [3] Int J modern Physics B **22**, 2617-2673 (2008)

ID: 103
Abstract Submissions
Topics: Planetary Tectonics & Impact Cratering

Testing different mechanisms of long-term crustal modification of large impact craters inferred from scaled analogue experiments.

Jan Oliver Eisermann, Ulrich Riller

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Although mechanisms of large impact cratering have been studied intensely, mostly by numerical modelling and field analyses, structural effects of long-term crater modification, operating on time scales of tens of thousands of years, are understudied. Localized deformation in the form of prominent crater floor fractures (CFFs) are known from large craters on all rocky celestial bodies. On Earth, large craters, such as Sudbury (Canada) and Vredefort (South Africa), CFFs are radial and concentric and filled with impact melt rock. Similarly, fractured crater floors are prominent post-cratering structural vestiges of lunar impact craters. Two mechanisms were proposed to explain the formation of CFFs: emplacement of horizontal igneous sheets into, and long-term isostatic re-equilibration of, target rocks below crater floors.

Using scaled analogue experiments, we systematically explored the structural consequences of both mechanisms on long-term crater floor deformation. The experiment surfaces were monitored with 3D digital image correlation allowing us to quantify key structural parameters, such as surface motion as well as the distribution and evolution of surface fractures. The results of our scale models enabled us to quantify the duration, geometry and distribution of brittle deformation of upper crust. Most importantly, the analogue experiments provided, for the first time, a quantitative relationship between diameter, depth and fracture geometry of crater floors.

Generation of horizontal igneous sheets, modelled by fluids injected into flat balloons emplaced in granular material simulating upper crust, caused radial and polygonal patterns of dilation fractures in the granular material. Fracture patterns were more controlled by the depth to the top surface of model sills rather than by crater floor morphology. Surface uplift and fracture formation was focused in model crater centers, potentially allowing magma to erupt from natural sill reservoirs below crater floors. In our experiments, magma evacuation is simulated by deflating balloons. This process generated concentric normal faults at the inner crater rims, which adheres to the presence of terraced crater margins ubiquitously observed at lunar craters. Interestingly, model craters are characterized by more diverse fracture patterns, compared to lunar craters. It is, therefore, unlikely that natural sill systems attain the structural maturity of our experimental equivalents. Hence, magma evacuation during inflation can account for the presence of less prominent fracture patterns in natural systems, compared to the ones in modelled, more “mature” sill systems.

Regarding experiments tailored to exploring long-term isostatic re-equilibration of crust below craters, our results indicate CFF formation by long-term crater floor uplift. Crustal re-equilibration is compensated by lower crustal flow toward the crater center and overall radial stretching of upper crust below craters. The latter generated radial and concentric dilation fractures. Crater floor uplift is accompanied by long-wavelength subsidence of the crater periphery. Specifically, the formation of radial versus concentric fractures depends on the ratio between crater diameter and crater depth and, hence, is controlled by crustal strength. Overall, the geometry and distribution of fractures in both types of analogue experiments are strikingly similar to the geometry of observed CFFs and renders long-term crater modification as an important structural process.

ID: 104

Abstract Submissions

Topics: Planetary Tectonics & Impact Cratering

Tectonic history of the Tharsis Rise on Mars inferred from wrinkle ridges: multi-stage plume activation and critical taper dome

Oguzcan Karagoz, Thomas Kenkmann, Stefan Hergarten

Institute of Earth and Environmental Sciences, Albert-Ludwigs-Universität Freiburg, Germany; oguzcan.karagoz@geologie.uni-freiburg.de

The Tharsis Rise (3500 km diameter), the largest volcano-tectonic province on Mars, is a notable volcanic region characterized by its broad and elevated topography, and it plays a key role in controlling the global tectonic pattern of the planet. This region has been evolving over the past four billion years, with certain areas exhibiting recent volcanic activity [1,2]. Early studies suggest that its formation can be attributed to a series of geological processes, including isostatic uplift followed by flexural loading, the accumulation of volcanic deposits, and crustal thickening through intrusion [2-6].

Here we decipher the uplift history of the Tharsis Rise utilizing wrinkle ridges. Wrinkle ridges are common tectonic landforms that serve as paleo-strain and paleo-stress indicators for the compressional history and thermal evolution of Mars [7]. They are positive relief linear to sinuous landforms that can be tens to hundreds of kilometers long, sometimes bifurcating, discontinuous, or forming en-echelon arrays [8]. In this study, we examined the system of wrinkle ridges that concentrically encircle the Tharsis Rise. Our research focused on reconstructing the center of the Tharsis Rise and its migration with time. We conducted a comprehensive mapping of wrinkle ridges around the dome's periphery. Our analysis encompassed 34,741 segments of wrinkle ridges, totaling 77,294 kilometers in length. We assessed the deviation of each wrinkle ridge segment from a concentric strike direction, focusing on centers that systematically shifted. The results from our fitting procedure revealed that the wrinkle ridge segments correspond closely to five distinct stress centers (C1-5) within the Tharsis Rise: near the southern boundary of Alba Mons' caldera (C1), the Ceraunius Fossae region (C2), the area between Ulysses Patera and Pavonis Chasma (C3), the vicinity of Phoenicis Lacus (C4), and around Claritas Rupes (C5). We performed morphometric analyses and kinematic modeling on each wrinkle ridge to quantify the degree of shortening and the depth of the detachment faults. Our calculations indicate that horizontal shortening ranged from 1.5 km to 3.8 km, while detachment depths varied between 2.9 km and 8.8 km, forming an acute wedge with an angle between 1.2° and 2.2°. We calculated extremely low basal friction coefficients, ranging from 0.077 to 0.093, across the detachment zones for these five centers. This suggests that the detachments are likely situated along layers of salt or clay, or in regions where liquid water predominates beneath a non-permeable permafrost layer and produced a fluid overpressure.

References

[1] Carr, M. H., & Head, J. W. (2010) *EPSL*, *294*,185-203. [2] Dohm et al. (2001) *JGR*, *106*, 32943–32958. [3] Banerdt et al. (1982) *EPSL.*, *87*, 9723. [4] Solomon, S. C., & Head, J. W. (1982) *JGR*, *87*, 9755 [5] Thurber, C. H., & Toksöz, M. N. (1978) *JGR*, *5*, 977-980. [6] Willemann, R. J., & Turcotte, D. L. (1982) *JGR*, 87,9793. .[7] Karagoz et al. (2022) *Icarus*, *374*, 114808. [8] Watters, T. R. (1988) *JGR, 93*, 10236-10254.

ID: 105

Abstract Submissions

Topics: Experimental Rock Mechanics, Modelling Deformation from the Micro- to the Mega-Scale

Insights into the deformation pattern and the edifice stability of oceanic volcanoes from direct shear experiments and finite-element models: A case-study of Anak Krakatau (Sunda Strait, Indonesia)

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Since volcanoes are fast-growing structures it is often thought that they are unstable and therefore prone to failure. Moreover, the lateral collapse of volcanoes has been observed worldwide and is evident from the geologic past. Such a lateral collapse is hazardous for the population living in coastal areas since the collapse of an oceanic volcano can lead to the generation of a tsunami. One recent example is the lateral collapse and tsunami of Anak Krakatau (Sunda Strait, Indonesia) in December 2018. Even though the lateral collapse of oceanic volcanoes is known to be a hazardous event, the precursors of such an event are poorly understood. At Anak Krakatau, long-term deformation of the SW-flank, which later collapsed, is evident from InSAR data and preceded the lateral collapse at Anak Krakatau. However, the connection between both processes is not known. To evaluate the impact of the external triggers and the connection between long-term flank sliding and the lateral collapse it is important to investigate the internal state of stability of a volcano. We have carried out direct shear experiments on ash and scoria samples from Anak Krakatau, which are the two main lithologies, and implemented the results into two-dimensional plain-strain finite-element models. The results show that in order to reproduce the long-term sliding of a volcanic flank, a pre-existing sliding plane within the volcanic edifice is needed, and a volcano without a sliding plane deforms predominantly through gravitational spreading. Thus, a sliding plane in the edifice of Anak Krakatau could explain the long-term deformation. The direct shear experiments tested on powdered gouge, show velocity-weakening behavior for both materials independent of the applied normal load and whether they were tested under water-saturated or dry conditions. Hence, it would have been possible for the flank of Anak Krakatau to have failed catastrophically along such a sliding plane. However, it is evident from the numerical models that the volcano, independent of the consideration of a sliding plane, is most likely a stable structure, in contrast to what has been suggested to far. The model results show that failure occurs only under unlikely conditions, i.e., extremely low cohesion, low friction coefficients, and an unrealistically high fault dip. Thus, we infer that an external trigger was likely needed to cause a collapse. How an external trigger can cause the collapse, and if the slow-sliding is actually connected to the collapse of the flank or whether it is an independent process, needs further research.

ID: 106
Abstract Submissions
Topics: Modelling Deformation from the Micro- to the Mega-Scale, Planetary Tectonics & Impact Cratering

3D structural analysis of symmetric, asymmetric, and double-ridges wrinkle ridges on Mars

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Wrinkle ridges represent one of the most common landforms observed on terrestrial planets, including Mercury, Venus, Mars, and the Moon. They are characterized by highly variable, positive relief and by linear, sinuous to discontinuous ridge morphologies; sometimes they form bifurcated or en-echelon systems. They can be hundreds of meters high and several tens of kilometers wide and are commonly interpreted as folds overlying blind or non-surface breaking thrust faults.

On Mars, wrinkle ridges are commonly formed on flood basalt-like units on volcanic plains and within large impact basins. Their morphological and structural analysis can give valuable insights into the geology of Mars, such as the lithospheric stresses and strain, and crustal mechanical stratigraphy.

Wrinkle ridge formation is still under debate, and several unresolved questions are waiting to be answered, including: i) their thin- or thick-skinned nature, ii) the geometry and likely structural style of associated blind faults, iii) fault dip angles and depth, iv) the number and role of faults, and (v) the amount of shortening accommodated by both faulting and folding. Various methodologies, such as elastic dislocation modeling, boundary element modeling, and balancing techniques (Watters, 2004; Okubo and Schultz, 2004; Karagoz et al., 2022), are proposed to address these questions. However, the 2D nature of these approaches leads to a lack of lateral variations and faults complexities.

In this work, a 3D geometrical reconstruction of a set of wrinkle ridges situated at Lunae Planum and Solis Planum (Tharsis Rise area) is performed by using the Move software package (Petex). This allows us to analyze and reproduce the 3D structural and morphometric characteristics. The case studies are chosen based on the availability of specific morphometric properties, which are supposed to be related to specific types of wrinkle ridges. Adhering to the most recent wrinkle ridge classification proposed by Andrews-Hanna (2020), we chose a few representative examples of each wrinkle ridge, including symmetric, asymmetric, and double ridges. We prioritized topographic data with a homogeneous resolution, thus we use the Mars Orbiter Laser Altimeter (MOLA) as the primary topography source, with further use of the Context Camera (CTX), aimed at better understanding smaller features (e.g., craters, faults complexities at their tips).

To perform the forward modelling, we combine the Trishear and Fault Parallel Flow algorithms, which can model complex fault geometry characterized by plane-strain deformation. The modelling assumes the presence of a triangular zone radiating from the fault tip, characterized by non-uniform deformation; within the triangle zone, layer thickness and length can change during deformation, but the area is kept constant. To determine the fault geometry that best fits the observed topography and the measured outcropping fault dip angles we perform root mean square error (RMSE) analysis of the modelled topography with respect to the MOLA data.

The presented forward modelling allows us to extract information regarding the 3D geometry (dip, depth) of the fault as well as the amount and distribution of accommodated shortening, which we use to discuss the possible rheological properties of Mars.

ID: 107

Abstract Submissions

Topics: Microstructures, Deformation Mechanisms & Rheology

Seismic induced anisotropy and kinking in quartz

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Recognition of seismically induced microstructures is important to unravel the different deformation processes during seismic cycles, especially at the base of the upper crust where many earthquakes nucleate. Deformed quartz veins related to a strike-slip shear zone within the Schobergruppe (Austroalpine Crystalline Complex, Eastern Alps) contain intense kinking in elongated quartz grains. The kink band boundaries are inclined into the general dextral sense of shear. Cathodoluminescence (CL) images reveal that the entire thin section contains a very high density of intragranular, sub-planar microstructures developed as thin dark CL lamellae accompanied with nanometre-scale fluid inclusions. Based on the oscillating orientation variation across low angle boundaries (misorientation angle 1-9°) these lamellar microstructures are referred as short-wavelength undulatory extinction microstructures - SWUE (Trepmann & Stöckhert, 2013). Only grains with SWUE, orientated parallel to the foliation, are kinked. In general, kinked microstructures mainly develop in strongly anisotropic material or minerals with a strong cleavage, e.g. micas. Deformation at high differential stresses e.g. during coseismic loading can produce a strong anisotropic microstructure in quartz by the development of deformation lamellae. Trepmann & Stöckhert (2013) showed in deformation experiments of quartz that SWUE preserve evidence of an earlier coseismic stress peak, even when overprinted during subsequent crystal plastic creep deformation at lower stress. The SWUE in the deformed Schober quartz veins are interpreted in a similar way. These microstructures were primary deformation lamellae developed during coseismic loading. TEM images reveal a high degree of recovery (low dislocation density) across the SWUE. Subsequent overprint by ongoing creep at lower stresses is recorded by vein quartz samples with mylonitic microstructures. The densely spaced sub-planar microstructures cause a high anisotropy of the quartz grains, which finally were kinked. Electron backscatter diffraction data give evidence of different slip systems that were active during the development of the deformation lamellae followed by recovery (SWUE), and during the subsequent kink band formation. The opposite direction of the Burges vectors (based on Weighted Burges Vector analysis, Wheeler et al., 2009) at the corresponding kink band boundaries is geometrical consistent with sinistral shearing within the kink domain along the anisotropic deformation lamellae/SWUE related to the dextral sheared kink band. Intensively kinked micas (muscovite and biotite) in the mica-rich host rock (in direct contact to the kinked quartz vein sample) point to seismic induced kinking, which is supported by the vicinity (1-1.5m) of a fault zone with pseudotachylytes (Bestmann et al., 2021).

Bestmann et al., 2021. Influence of Deformation and Fluids on Ti Exchange in Natural Quartz. *J Geophys Res, Solid Earth, 126.*

Trepmann & Stöckhert, 2013. Short-wavelength undulatory extinction in quartz recording coseismic deformation in the middle crust – an experimental study. Solid Earth, 4, 263-276.

Wheeler et al., 2009. The weighted Burgers vector: a new quantity for constraining dislocation densities and types using electron backscatter diffraction on 2D sections through crystalline materials. *J Microscopy, 233, 482–494.*

ID: 108

Abstract Submissions

Topics: Microstructures, Deformation Mechanisms & Rheology

Microstructural evolution of a 40 year old crushed salt backfill - Quantitative microstructural analysis

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Crushed salt (CS) is regarded as the most favourable geotechnical barrier material for isolating radioactive waste within rock salt formations, because it is expected to compact to a low porosity/permeability during cavity convergence, similar to that of the surrounding intact rock salt.

The evolution of CS during compaction within a converging cavity, under in-situ repository conditions, is still under investigation, both in laboratory and underground experiments, as well as in computational forecast modelling. To achieve low porosities within relatively short-term laboratory experiments (<2 year), stresses are typically higher than expected in-situ, and deformation mechanism may differ in importance. This contrast raises uncertainties in extrapolation of laboratory compaction and sealing rates to in-situ conditions.

Numerical models need to accurately predict whether compaction is sufficiently rapid to prevent radioactive nuclides from escaping the repository, once the integrity of the storage container can no longer be guaranteed. Further, they define the minimal lifespan of drift sealing elements that need to act as a barrier before CS has sufficiently been compacted. To assess if the relevant deformation mechanisms are considered and therefore the correct compaction behaviour is modelled, validation is needed - by testing if the deformation microstructures developed in naturally compacted mine backfill match those seen in experiments.

We present results on a CS backfill compacted to a few percent porosity by 40 years of naturally slow convergence of a cavity within the Sigmundshall mine, Bokeloh, Germany. Previous microstructural work on the material indicated a major contribution of diffusive mass transfer (DMT), in particular by pressure solution [1]. Pressure solution is generally much faster in fine-grained materials. Surprisingly, preliminary SEM/optical analysis of 2417 segmented grains in a polished section revealed no clear grain size dependent differences in circularity, axial ratio or rugosity. To assess the role of pressure solution numerically, the measured grain size distribution was imported to a grain-size sensitive creep model [2]. The predictions of this model (evolution of porosity and strain rate), were compared to a triaxial test on material adjacent to the analysed sample, performed at near in-situ mean stress (7.1 MPa) and low differential stress (1.5 MPa) lasting for 60 days. Although the drilled CS backfill showed a small pycnometry-derived porosity (1 % ±4 %), the test data showed signs of both, compaction and deviatoric creep.

In this contribution, we discuss (1) the differences between our numerical prediction and laboratory creep results and (2) the results of a numerical calculation of 40-year long compaction of CS by pressure solution under in-situ Sigmundshall conditions, versus the porosity reduction of about 35 % observed in this material. Backed by findings on microstructural deformation indicators, the (chronological) impact of different mechanisms on this compaction process is presented.

References:

[1] Svensson , et al., In preparation. Microstructural evolution of compacted crushed salt: insight from 40-year-old backfill at the Sigmundshall potash mine (Germany).

[2] Van Oosterhout et al., In preparation. Effect of stress, grain size distribution and porosity on the compaction behavior of granular salt: implications for repository backfill sealing timescales

ID: 109

Abstract Submissions

Topics: Seismo-Tectonics & Fluid-Rock Interaction, Neo-Tectonics & Tectonic Geomorphology

Active Faults in Kurdistan, Northern Iraq

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This study presents some cases of seismic activities caused by the Quaternary reactivation of Late Precambrian blind basement faults in the Sinjar, Zakho, Sheladiz, Raniya, and Shaikhan areas. These locations are situated within the Zagros fold-thrust belt in the Kurdistan region of northern Iraq, near the north-eastern margin of the Arabian plate. Iraq is characterized by low- to moderate-magnitude earthquakes with shallow focal depths. Kurdistan is the most active region in Iraq due to its position near the Bitlis-Zagros suture zone, and most of its seismic activity is attributed to the neotectonic reactivation of many seismically active blind basement faults that locally occur close to the surface as major faults or well-defined structural and topographic lineaments. The inferred seismogenic faults in the Sinjar, Zakho, Sheladiz, Raniya, and Shaikhan areas were formed in the Late Precambrian, repeatedly reactivated throughout the Phanerozoic time, still active at the present-day and has the potential to generate major earthquakes in the future. The rotational optimization method (Windows-Tensor software) was used to determine the present-day stress field by inversion of the fault plane solutions. The stress inversion results indicate a predominant of NNE to SSW oriented maximum compressive stress ($\sigma1$) in the study area. This present-day dominant direction supports the active shortening across the Zagros fold–thrust belt due to the Mid Miocene continental collision between the Arabian and Eurasian plates. The findings of the present study may offer more clues to predict where future earthquakes are most likely to occur.

ID: 110

Abstract Submissions

Topics: Seismo-Tectonics & Fluid-Rock Interaction, Applied Structural Geology

The “Restless”-Project: Investigating the impact of lithology on the risk of induced seismicity in deep geothermal reservoirs

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One of the key issues determining public acceptance of the energy production from deep geothermal reservoirs is the avoidance of induced seismicity. In this context the project “Restless”, funded by the German Federal Ministry for the Economy and Climate Protection (BMWK), will analyze and try to quantify possible influences of the reservoir lithology on the risk of induced seismicity in deep geothermal wells. A particular focus will be on fracture-controlled reservoirs in locations like the Upper Rhine Graben (URG) and on differences between crystalline and Mesozoic sedimentary rocks. For this purpose the project combines field, laboratory and numerical modeling methods, in particular (1) quantification of structure and kinematics of faults in relevant reservoir rocks based on outcrop studies and on geophysical and hydraulic well data, (2) palinspastic reconstructions of tectonically deformed structures to quantify off-fault deformation, (3) characterization of mechanical properties of reservoir rocks, in particular their frictional properties, (4) numerical modeling of stress evolution and fault reactivation potential resulting from the operation of a geothermal doublet at multiple scales, and (5) numerical simulation of induced seismicity using Thermo-Hydro-Mechanical (THM) models and calculation of the resulting ground motion to estimate seismic risk. The numerical simulation workflow will be applied to a test site in the Upper Rhine Graben. Given the importance of public acceptance for the increased use of geothermal energy, outreach and dissemination of the project results to the general public is also an integral part of the project.

At the end of the project, the combined results of these various sub-studies should provide a better understanding of which reservoir lithologies and structures are feasible targets for geothermal energy extraction with the minimum risk of perceptible induced seismicity.

ID: 111

Abstract Submissions

Topics: Microstructures, Deformation Mechanisms & Rheology, Experimental Rock Mechanics

Implications for the strength of the Earth’s middle crust from novel experiments on natural fine-grained granitoid rocks

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To comprehend the rheology of the Earth's crust and the relevant rock properties, one key approach is to deform rocks and minerals at elevated pressures and temperatures and then extrapolate the measured stress and strain rate values to natural conditions using constitutive equations. Laboratory experiments are mostly conducted on monomineralic rocks, with quartz being considered as the weakest constituent of the middle continental crust. However, field observations suggest that this is an oversimplification, and polymineralic fault rocks may be weaker than monomineralic quartz rocks. This study presents the first experiments on fine-grained, solid, natural rock samples, containing their natural homogeneities and inhomogeneities, demonstrating that granitoid rocks may be weaker than quartz at mid-crustal conditions. It also highlights the importance of pre-existing faults and polymineralic fine-grained zones for strain localisation and proposes values for extrapolation to natural conditions and their use in numerical models of the deformation of the granitoid crust.

Cylindrical granitoid ultramylonite samples, composed of qtz + ab + K-fsp + bt + ep, with grain sizes of 125-15 µm are deformed in a Grigg’s type apparatus at T=650°C, confining P=1.2 GPa, strain rates=10^{-3} to $10^{-5}s^{-1}$, and 0.2 wt% H_2O added. Mechanical data are combined with light microscope, SEM, TEM, and quantitative image analysis to connect microstructures with stress and strain evolution. We show that polymineralic granitoid rocks deform through other mechanisms than monomineralic quartz aggregates at pressure and temperature conditions characteristic for the middle crust: Ultra-fine grain size reduction down to <50nm is developed by nucleation and growth of new grains in a polymineralic mixture. Grain size remains small because of pinning processes. We therefore refer to the deformation mechanism as pinning-controlled dissolution-precipitation creep (P-DPC).

Furthermore, we establish a new constitutive equation for this P-DPC, based on an exponential diffusion creep flow law, to model our experiments and tackle the extrapolation to various natural conditions. This flow law is supported by the microstructural evidence for the deformation mechanisms. Extrapolations show that the shear zones of the granitoid middle crust may be magnitudes weaker than extrapolated so far, and deformation may occur at magnitudes faster rates. The brittle to viscous transition may be shifted to shallower levels. This may have implications for the seismogenic zone and/or stress fields below geothermal reservoirs. Most importantly, we show the necessity to take polymineralic rocks into consideration for various numerical model applications.

ID: 112
Abstract Submissions
Topics: Experimental Rock Mechanics, Metamorphism & Deformation

Transformative insights into reacting, deforming rocks through operando x-ray imaging experiments - elastic stress control on fabric formation and fluid transport properties

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The macro scale tectonic evolution of rocks is ultimately controlled by chemical, hydraulic and mechanical developments on the micro scale. In many cases, these developments are coupled, and different processes affect and feedback on each other. Where feedback loops emerge, they may trigger instabilities that propagate up-scale. Previously, our understanding of chemical-hydraulic-mechanical feedbacks in deforming, reacting rocks has suffered from experimental constraints, which restrict the documentation of relevant processes to indirect measurements and post-mortem evaluations. We show how operando x-ray imaging can be used to overcome these severe limitations and enable the direct, time-resolved observation and quantification of coupled developments and feedbacks on the micro scale.

We focused on the dehydration of Volterra alabaster to explore chemical-hydraulic-mechanical coupling in the evolving samples. While being directly relevant in thin-skinned tectonics and the evolution of fold and thrust-belts, gypsum dehydration is also considered a model reaction for prograde metamorphic processes in subducting serpentinites. The dehydration of gypsum to bassanite is temperature- and pressure sensitive, and the reaction will stall where the released pore fluid cannot drain through porosity that emerges during the reaction but potentially compacts in a deforming sample. We used an x-ray transparent triaxial deformation rig deployed at the Swiss Light Source, the French Synchrotron SOLEIL and the UK's Diamond Light Source to document the effects of differential stress and pore fluid pressure on the formation of bassanite and pores from gypsum in 4-dimensional µCT datasets. Our experiments permitted linking indirect measurements of bulk strain and fluid expulsion with direct micro-scale observations from the reacting and deforming samples. A novel deep-learning-based image segmentation workflow allowed the precise quantification and tracking of the volume, distribution, and orientation of gypsum, bassanite and pores in the sample. The segmented image data formed the basis for flow simulations that yielded quantitative estimates of the evolving permeabilities in dehydrating, deforming samples at different stress boundary conditions. Our data illustrate how the application of differential stress causes the oriented nucleation of bassanite grains and pores in the deforming sample at negligible macroscopic elastic strains. This controls the emergence of strongly anisotropic permeability. The combination of bulk strain- and pore fluid volumetric measurements with the grain scale quantifications from the 4DµCT data shows that elastic stresses can form metamorphic fabrics entirely without the need of large irrecoverable deformations.

Our data illustrate how, precisely, chemical, mechanical and hydraulic processes are coupled on the grain scale and allow the quantification of the temporal- and spatial length scales of the emergent feedback loops. We demonstrate how 4DµCT data hold the key to understanding micro scale controls on macro scale developments in tectonics, but also in other research where fluids interact with rocks.

ID: 113
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Basin formation caused by plate boundary-parallel extension, Island of Rhodes, Greece

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Crust underlying the Island of Rhodes is part of the forearc of the eastern Hellenic subduction zone. Deformation of the forearc rocks appears to be influenced mostly by oblique plate convergence, subduction roll-back and horizontal-axis rotation, the relative importance of these processes is not well known. The southeast coast of Rhodes hosts Pliocene to Pleistocene marine strata, which have been attributed to fault-controlled basin formation. However, it is poorly understood how faulting is intertwined with deposition of marine strata and how basin formation relates to the first-order tectonic processes. To examine this relationship in detail, the Lardos area was selected, due to its excellent exposure of marine sedimentary strata and fault scarps. We studied the deformation of this area on multiple scales employing remote sensing as well as lithological and structural mapping. Moreover, differential GPS and drone imagery were used to assess fault displacements based on offset marine terraces and lithological boundaries.

A digital elevation model and satellite images revealed the presence of prominent N-, NW- and NE-striking geomorphological lineaments. In the Lardos area, these lineaments were identified as traces of kilometre-scale faults cutting Mesozoic to Paleogene strata. Mapping of sedimentary rocks on either side of pairs of fault scarps indicates that the scarps are normal faults forming the margins of an elongated basin hosting Pleistocene marine deposits. Notably, a sedimentary breccia, consisting mostly of Pre-Pleistocene carbonate rock clasts embedded in a fine-grained matrix of Pleistocene sediments, lines the fault scarps. Differential GPS measurements and drone imagery demonstrated that the prominent faults displaced the lithological contacts between Pleistocene and pre-Pleistocene lithologies as well as the marine terraces. Furthermore, dilation bands and deflected bedding in the proximity of the faults were recognized within the Pleistocene marine deposits.

Collectively, these observations point to the following sequence of tectono-sedimentary stages of basin formation: Normal faulting initiated the Pre-Pleistocene opening of a basin interpreted as a graben. Based on the occurrence of the sedimentary breccia along the fault scarps and displaced Pleistocene marine terraces, the graben-bounding normal faults continued to be active during and after the Pleistocene. Faulting affected Pre-Pleistocene carbonate rocks and the unconformably overlying Pleistocene marine sedimentary strata. During uplift of the southeast coast of Rhodes, marine terraces formed and reshaped the paleo relief. Graben formation in the study area can be attributed to overall ENE-WSW, i.e., plate boundary-parallel, extension of the forearc rocks. This extension direction can be explained by increasing crustal stretching along the forearc as a consequence of progressive tightening of the curved Hellenic subduction zone.

ID: 114

Abstract Submissions

Topics: Planetary Tectonics & Impact Cratering

DYNAMIC STRENGTH, FRAGMENTATION, AND THE IMPACT CRATERING PROCESS

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During impact cratering, target materials are subjected to extreme deformation conditions. Brittle deformation under these conditions, where strain rates can exceed 10^2 s^{-1}, is rate sensitive. Typically, rocks are stronger when deformed at high strain rates. This occurs because fracture propagation has a limited velocity; at high loading rates, the weakest flaws in a material are not able to cause failure before other, increasingly strong flaws are activated. This results in significant changes to mechanical properties and causes fragmentation. Dynamic compressive strength and fragmentation in brittle materials may have important consequences for the properties of impact-deformed rocks and the scaling of impact craters.

Here, we present results of high strain-rate mechanical tests to determine the characteristic strain rate for rate-dependent brittle failure and strength increase, and the fragment size and shape distributions that result from failure at these conditions. We investigated a variety of rock types and considered whether the fragment characteristics can be used as diagnostic indicators of loading conditions during brittle failure. Mechanical data and fragmented samples were obtained using a hydraulic loading frame and a split-Hopkinson pressure bar (SHPB). The hydraulic loading frame achieves strain rates from 10^{-6} s^{-1} to 10^{-4} s^{-1}, while the SHPB achieves strain rates from 10^1 s^{-1} to 10^3 s^{-1}. We focussed our micro-structural analysis on the distributions of fragment size and fragment shape as functions of strain rate.

We find that the characteristic strain rates of rocks, where the dynamic strength is twice the quasi-static strength, ranges between ~150 and ~350 s^{-1} depending on lithology. Fragment size analysis demonstrates an inverse power-law relationship between fragment size and strain rate for dynamic failure under uniaxial compression. Unlike fragment size, we find that fragment shape is independent of strain rate under dynamic uniaxial loading.

Numerical impact simulations demonstrate that strain rates are sufficiently high to produce rate-dependent effects in planetary impacts where impactor diameters are ~100 m or smaller. Rate-dependent strength and fragmentation therefore plays an important role in small planetary impacts and laboratory impact experiments. However, rate-dependent strength is not widely implemented in present-day numerical impact simulations. We use the results of our mechanical tests to develop a semi-empirical approach to account for rate-dependent shear and tensile strength in numerical impact simulations. We benchmark our model against experimental impact craters from the MEMIN research unit, demonstrating that rate-dependent strength is required to explain the dimensions of laboratory-scale impact craters. Furthermore, we show how rate-dependent strength affects impact crater scaling for small, strength-dominated craters, without influencing scaling in the gravity regime.

In summary, our results demonstrate that rate-dependent brittle fragmentation and strength play an important role in the impact cratering process. We have developed a rate-dependent strength model required to accurately benchmark numerical impact simulations against laboratory-scale experiments. Furthermore, our results show that fragment size may be used as a diagnostic indicator of the strain rate at failure during impact loading while fragment shape cannot be used.

ID: 115
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Variation of principial strain axis directions with proximity to first-order fault zones and its importance for elucidating forearc deformation on the Island of Rhodes, Greece

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Kinematic analysis of small-scale shear faults is ubiquitously applied to infer principal strain directions in brittlely deformed terrains. Often, the directions vary greatly with the locations of fault-slip measurements. In such areas, non-uniform principal strain directions are frequently interpreted as evidence for the presence of individual and successive deformation regimes. Due to the pervasive coverage of multi-scale brittle faults, the Cape Archangelos area at the south coast of Rhodes lends itself to testing the validity of this practice. Here, kilometer-scale, surface-morphological lineaments, demarcating the traces of oblique normal faults, are considered as first-order faults regarding higher-order, meter- to decameter-scale shear faults. Collectively, the faults affect Plio-Pleistocene marine strata and, thus, adhere to neo-tectonic deformation. This allows us to test to what extent principal strain axis orientations, inferred from the inversion of higher-order shear faults, are influenced by their proximity to first-order normal faults. Our analysis of the neo-tectonic strain field is based on the extraction of some 80 normal faults from digital surface models and inversion of 365 higher-order brittle shear faults at 14 stations.

First-order normal faults form two sets, one striking NNE, the other NNW. As it is unlikely that the overall deformation regime changed during Plio-Pleistocene to Recent times to consecutively have formed the sets, both sets are interpreted as conjugate. Hence, the normal faults formed under the same deformation regime, generally characterized by NE-SW horizontal extension. Based on the inversion of higher-order shear faults, rudimentary strain tensor solutions were calculated and indicate either overall N-S or E-W horizontal extension. It is noteworthy that fault populations at each station were found to be kinematically homogeneous, which is consistent with the notion above that they formed under a single deformation regime. Most interestingly, half of the stations indicating approximately E-W extension are located on or close to first-order normal faults, whereas the other stations showing chiefly N-S extension may be located as much as hundreds of meters away from these faults. We conclude that the presence of first-order structural discontinuities can significantly influence principal strain axis directions.

Knowledge of principal strain axis directions on the island of Rhodes is paramount for better understanding its geodynamic setting. Rhodes constitutes an exposed forearc portion of the eastern Hellenic subduction zone, which is characterized by oblique subduction of African below Aegean lithosphere. The Hellenic subduction zone interface displays a strong curvature, the origin of which has been attributed to roll-back, orogenic collapse of Aegean lithosphere, and westward motion of Anatolian lithosphere. Along with oblique subduction, each of these processes generates specific principal strain axis directions. Overall NE-SW, and thus plate boundary-parallel extension, of forearc rocks at Rhodes, as indicated by first-order normal faults, crudely agrees with rudimentary strain tensor solutions at locations away from first-order faults and is best explained in terms of oblique subduction.

ID: 116
Abstract Submissions
Topics: General Tectonics & Regional Studies, Applied Structural Geology

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Thomas Degen

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ID: 117
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology, General Tectonics & Regional Studies

Kinematic evolution of the Ngwi area along the Pan-African Central Cameroon Shear Zone (Adamawa-Yadé domain): Implications for emplacement of the Ngwi granitic pluton

Ludovic Achu Megnemo[1], Eric Martial Fozing[1], Jules Tcheumenak Kouémo[2], Julios Efon Awoum[1], Belmien Robinson Sobze Yemdji[1], Maurice Kwékam[1]

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The Ngwi area in central Cameroon is part of the Adamawa-Yadé domain in the Pan-African Fold Belt of Central Africa (PBCA). It is dominated by granitic pluton (including biotite-muscovite granite and hornblende-biotite granite) emplaced along the southern margin of the Central Cameroon Shear Zone (CCSZ) within remobilized metasedimentary basement rocks made-up of paragneisses (including melting pocket of biotite-muscovite-garnet granite), banded para- and massive ortho-amphibolites. New field structural, microstructural and kinematic markers of the granites and metamorphic country rocks from the Ngwi area are analysed in order to decipher the detailed kinematic evolution of the Ngwi area and the emplacement model of the Ngwi granitic pluton alond the CCSZ in relation to the Pan-African regional tectonics. The Ngwi area has experienced three deformation events (D_1, D_2, and D_3). D_1 (622-613 Ma) is a NW-SE trending event of compressive tectonics related to the development of transposed S_1 foliation in paragneisses. D_2 (*ca*. 613-590 Ma) is a sinistral shear event initiated in the NE-SW direction and progressively rotated toward the NNE-SSW and locally toward the NW-SE. It developed dominant S_2 foliation in country rocks, synchronous to the magma emplacement (with development of Sm_2 magmatic foliation and syn-magmatic fabrics) and deformation (with development of shear bands cleavage textures). D_3 (585-540 Ma) is a NE-SW to ENE-WSW trending shear event displaying a dextral movement and has gradually rotated at NW-SE. The microstructures observed for quartz, feldspars and micas in granites confirm the presence of significant syn- to post-emplacement deformation, indicating a continuum from magmatic to sub-magmatic flow through sub-solidus recrystallization. This is consistent with syn-kinematic fabric development from high-temperature (*ca*. 700 °C, where melt-present deformation occurred) to low-temperature (<300 °C, where kinking of mica cleavages occurred) in granites, and therefore the development of deformation-induced textures between mid-amphibolite and lower greenschist facies conditions. The pluton and its metamorphic host rocks recorded sinistral to dextral sense of shear movement as established by the kinematic markers, consistently with the sinistral D_2 and dextral D_3 events of the kinematic evolution of the Ngwi area in the regional tectonic framework. The Ngwi pluton would have emplaced from early- to late-D_2 (with the emplacement of biotite-muscovite granite) sinistral regional deformation event (613-590 Ma) and ended at the late-D_3 (with the emplacement of hornblende-biotite granite) dextral regional event (585-540 Ma) of the tectonic history of CCSZ. This is consistent with the emplacement of the Ngwi pluton from the sinistral left lateral wrench movement through the dextral right lateral wrench movement of the tectonic history of PBCA in Cameroon. Syn-kinematic emplacement in dilatation jogs (tension gashes) opened in the paragneisses host rocks under transpressive tectonic is suggested as a plausible model for the emplacement of the Ngwi pluton along the CCSZ. Moreover, the presence of typical structures of a syn-kinematic intrusion or a post-magmatic ductile shearing (mylonitic fabric, S/C structures) in this Ngwi pluton confirms its emplacement into a high strain sheared crustal domain.

Keywords: Ngwi granites; Structures; Microstructures; Kinematic markers; Pluton emplacement; Central Cameroon Shear Zone; Kinematic evolution.

ID: 118

Abstract Submissions

Topics: Mountain Building Processes & Alpine Tectonics

Exploring the impact of inherited structures on deformation and uplift in fold and thrust belts through multi-scale analogue modelling: a case study in the European eastern Southern Alps

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Neogene to ongoing N(W)-directed continental indentation of the Adriatic microplate into Europe controls the evolution of the European eastern Southern Alps (ESA). The Adriatic microplate, traditionally considered as a rigid indenter, demonstrates significant internal deformation, with mostly Miocene shortening being accommodated within a WSW-ENE striking, S-vergent fold-and-thrust belt. The latter overprints a compositionally heterogeneous upper crust linked to Permian intrusives and extrusives and a pre-existing platform-basin geometry related to Jurassic extension.

We present new, multi-scale physical analogue experiments, to address the effect of lateral crustal heterogeneities on strain localization and deformation geometries of the ESA, which is key for establishing causal relations between crustal and lithospheric deformation and surface uplift patterns associated with Miocene basin inversion.

Brittle crustal-scale analogue experiments with inversion of pre-scribed platform-basin geometries, indicate that variations in thickness, shape, and basement structure have impact on timing and uplift of the ESA's upper crust. Our modelling results demonstrate that experiments with a stronger upper crustal domain (representing Permian volcanic rock on Jurassic platforms) show a smaller number of thrust sheets, being in line with thrust sheet geometries across the natural example of the ESA, and continuous uplift patterns. The latter is supported by continuous exhumation within the last 15 Ma documented by low-temperature thermochronology data between Mauls and Bassano (see contribution of Pomella et al.). The topographic evolution of the experiments is sensitive to a variation in crustal composition; additional, e.g., basement structures (modelled using a fixed basal plate whose boundaries represent Permian faults) result in limited uplift of northern model parts, which is consistent with documented little vertical movement of the western ESA north of the Valsugana fault system between Jurassic and Neogene times.

On the scale of the lithosphere, new analogue experiments with pre-scribed platform and basin geometries in the upper crust show similar lateral variations in thrust fault orientation across transfer zones as crustal-scale experiments (Sieberer et al., 2023). Variations in lithospheric strength lead to increasing wavelengths between thrust sheets in models with stronger rheologies, pre-existing heterogeneities in the upper crust to strain localisation at boundaries of strong domains. Additionally, lateral variability of ductile lower crustal thickness predicts stronger uplift in areas of thicker lower crust. A similar relationship has been documented for the northwestern ESA, where Miocene thickening of the lower crust is expected to correlate with higher uplift in the Tauern window (Jozi Najafabadi et al., 2022).

Jozi Najafabadi, A., Haberland, C., Le Breton, E., Handy, M. R., Verwater, V. F., Heit, B., Weber, M., 2022. Constraints on Crustal Structure in the Vicinity of the Adriatic Indenter (European Alps) From Vp and Vp/Vs Local Earthquake Tomography. Journal of Geophysical Research: Solid Earth, 127.

Sieberer, A.-K., Willingshofer, E., Klotz, T., Ortner, H., Pomella, H., 2023. Inversion of extensional basins parallel and oblique to their boundaries: inferences from analogue models and field observations from the Dolomites Indenter, European eastern Southern Alps. Solid Earth 14, 647-681.

ID: 119

Abstract Submissions

Topics: Planetary Tectonics & Impact Cratering

STRUCTURE OF THE MARINE TARGET IMPACT CRATER NADIR INFERRED FROM 3D-SEISMICS

Uisdean Nicholson[1], Thomas Kenkmann[2], William Powell[3], Sean P. S. Gulick[4], Veronica J. Bray[5], Pascoal Duarte[1], Gareth S. Collins[6]

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The number of newly discovered and confirmed impact structures on Earth is growing continuously (Gottwald et al. 2020; Kenkmann 2021, https://impact-craters.com). Of the ~210 impact craters known so far, only 33 show evidence for formation under marine or aquatic conditions through the presence of reworked breccia and resurge deposits filling the crater depression. Typical features of craters formed under submarine conditions are: (1) a nested crater morphology, with an upper crater formed in unconsolidated sediments that is enlarged by the water excavation and resurge, and a smaller sized central crater formed in consolidated target rocks, (2) the replacement of a clear crater rim by a broad brim zone, and (3) a thick sequence of resurge deposits within the crater depression, with indications of soft sediment deformation (Kenkmann 2021), and sorted, draped facies (Gulick et al. 2019).

Nicholson et al. (2022) proposed the discovery of a new marine impact crater – Nadir – that lies offshore West Africa within the continental shelf stratigraphy of the Guinea Plateau. This discovery was made on the basis of 2D seismic profiles of the region, and comparison of the structural deformation with that expected for a ~ 9 km diameter impact crater. Even though this work was limited to cross-sectional profiles of the Nadir crater, clear structural information was present, allowing for a good analysis of this impact crater. Drilling of the Nadir crater is planned in the framework of IODP3, to return rock samples necessary to definitively evaluate its status as an impact crater. Until then, its impact crater status relies on stratigraphy, structural geology, and morphology.

Nicholson et al. (2024/in press) present new 3D-seismic evidence from the Nadir Crater, providing exceptional new structural imaging, unprecedented for any terrestrial or extraterrestrial impact structure. The data interpreted so far reveal major new insights into the marine impact cratering process, including exceptional imaging of subsurface deformation, reconstruction of impact trajectory, the identification of a regional subsurface damage zone far beyond that interpreted previously for other impact craters of its size and seismic facies evidence for regional liquefaction and tsunami-seabed interaction.

Seismic data display concentric extensional faults across a broad area surrounding the crater. Deeper levels show concentric faults below the inner rim, which interact with reactivated NW-SE trending Early Cretaceous faults NE of the structure. The central uplift shows a bilateral axis of symmetry that we interpret to be parallel to the trajectory of the asteroid during impact. The less deformed periphery of the central uplift displays radial folds and reverse faults. These vergencies indicate the direction of mass transfer top to the west due to an oblique impact.

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Nicholson, U., et al. (2022) *Sci. Adv. 8,* eabn3096.

Nicholson, U., Powell, W., Gulick, S.P.S., Kenkmann, T., Bray, V.J., Duarte, D., Collins, G.S. (2024). *Sci. Adv. In press.*

ID: 120
Abstract Submissions
Topics: Metamorphism & Deformation, Geodynamics & Plate Tectonics

Large-scale anatomy of a deep subduction megathrust: observations from the Cycladic Blueschist Unit on Syros, Greece

Dominic Hildebrandt, Whitney Maria Behr, Jesús Muñoz-Montecinos, Leif Tokle

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Geological and geophysical observations characterize deep mixed brittle-ductile subduction shear zones as heterogeneous and structurally complex fluid-rich environments. In modern subduction zones this region hosts Slow Slip and Tremor (SST), which are transient slip events with strain rates between regular earthquakes and plate convergence associated with tremor. Although studies suggest that stress and fluid transfers may link the deep SST zone with the up-dip megathrust as source region of hazardous regular earthquakes, the processes underlying SST are poorly understood. A key problem is that the large-scale make-up of deep subduction shear zones with their multi-scale heterogeneities is not well characterized and therefore not available for assessing their rheological behavior. Here we report such data from the iconic HP-LT metamorphic rock record of the Cycladic Blueschist Unit exposed on Syros, Greece. Our study relies on field mapping, high-resolution drone surveys, 3D visualization and microscopic methods.

The Kampos Belt in the north of Syros is a ~ 3 km wide and up to 1 km thick rock pile inferred to represent a fossil deep subduction interface formed at blueschist to eclogite facies conditions. In the west, it consists of meta-basic lenses in a matrix of meta-volcaniclastic schists, Tr-Chl schists and serpentinites. Towards the east, weak matrix rocks are sparse and larger metabasite bodies dominate. Substantial heterogeneity in terms of lithology, grain size, mineralogy and structure is inherited from the pre-subduction rifted passive margin setting. Five ductile thrust faults mapped along the eastern coastline and the repetition of an inherited rifted passive margin stratigraphy in the central and western part suggest that tectonic underplating is another major heterogeneity source leading to across-strike variations on scales of 10s to few 100s of m. Moderate tectonic dismemberment and metasomatism further modified these heterogeneities and their length scales. Along-strike rheological variability occurs on scales of 1 to 2 km and might be controlled by different slicing depths during underplating. Block-in-matrix associations in the western and central part define another major source of mechanical contrasts, as highlighted by dm- to m-wide high-strain and metasomatic zones along block-to-matrix interfaces. Block sizes range from a few dm up to several 100s of m, with typical sizes between 1 and 5 m at this observational scale. Two clusters with high spatial block densities show along-strike lengths of ~ 600 m, consistent with calculated sizes of tremor-sourcing patches in modern subduction zones.

For the first time this study provides quantitative and qualitative geological constraints for multi-kilometer-scale heterogeneities of a fossil subduction complex. These data help to attribute observed seismic behaviors to fault characteristics and to refine and calibrate numerical simulations of SST.

ID: 121
Abstract Submissions
Topics: Metamorphism & Deformation, Geodynamics & Plate Tectonics

Metamorphic history and geodynamic significance of the MORB-derived amphibolites from the Bankim area in the Foumban-Bankim Shear Zone: evidence of subduction, late Paleoproterozoic.

Julios Efon Awoum[1], Maurice Kwékam[1], Eric Martial Fozing[1], Jules Tcheumenak Kouémo[2], Ludovic Achu Megnemo[1]

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MORB-derived amphibolites are locally embedded within Pan-African basement rocks, underlining Bankim xenoliths in the north-eastern part of the Foumban-Bankim Shear Zone (FBSZ). The present work show their petrological and geochemical variations. These amphibolites are sub-rounded and lenticular with mostly granoblastic microstructure, defining three main types: (i) a clinipyroxene-bearing amphibolite with mineral assemblage of Cpx + Hbl + Pl + Ttn, (ii) garnet-bearing amphibolite with mineral assemblage of Grt + Pl + Hbl + Ttn + Opq + Qtz, and (iii) biotite-bearing amphibolite with mineral assemblage of Hbl + Pl + Bt + Ttn + Opq + Ep. In this mineral association, clinopyroxene and garnet oftern surrounded by plagioclase and the whole is rimmed by large crystals of hornblende, then defining kelyphitic and coronitic microstructures respectively. Two metamorphic phases, prograde and retrograde, are responsible of the observed microstructures which are interpreted as the result of the following mineral transformation: **basalt ---> amphibolites ---> eclogites ---> amphibolites** as describe in convergent zone. P-T estimates indicate that the amphibolites reached peak metamorphic conditions of 13-16 kbar and 800-1000°C. Almandine becomes enriched in pyrope components with increasing temperature and high pressure. Partial replacement of almandine-rich garnet by edenite and pargasite or sometimes by magnesio-hornblende, reflects a high-pressure metamorphic event followed by rapid exhumation. Their geochemical patterns are of MORB-type without Ce anomaly, displaying important Ta and Yb negative anomalies. They are ortho-amphibolites with gabbroic composition. The field relationship, the metamorphic history and the petrological data suggest a formation during subduction as already proposed for the Central Cameroon Shear Zone.

Keywords: Amphibolites; Metamorphic phases; Bankim; Central Cameroon Shear Zone; Subduction.

ID: 122
Abstract Submissions
Topics: Planetary Tectonics & Impact Cratering

Comprehensive structural and petrographic analyses of drill core samples from the center and rim of the small (60 x 41 m) impact crater SM-1 of the Wyoming crater field, USA

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With a size of 60 x 41 m, the impact crater SM-1 (lat 42.65°N / long 105.45° W) is one of the larger craters of the Wyoming crater field, formed 280 myr ago (Kenkmann et al. 2022). Its impact origin was proven in 2018 by the discovery of several impact-related shock effects (e.g., planar deformation features) in Casper sandstone samples taken inside and outside of the crater structure (Kenkmann et al., 2018a, 2022). In September and October of 2022, two boreholes were drilled vertically into the subsurface inside and outside of SM-1. The first borehole, called SM-1-Y, was drilled into the center of the crater, down to 7.14 m depth. The second borehole, called SM-1-Z, was drilled slightly outside of the present-day rim, down to 27.44 m depth. From both boreholes, drill cores with diameters of 4.8 cm were successfully extracted. Both drill cores were sawed vertically into four parts, of which one quarter was used for thin section preparation and structural mapping. Standard polished thin sections were manufactured from 10-15 cm spacings to investigate the degree of shock metamorphism and cataclastic deformation. To study the fracture network and the orientation of the sedimentary layering, a series of 3D virtual models of selected drill core samples were processed following the principles of photogrammetry. The core sample was positioned above a rotating plate, and photos were taken every 10° of rotation. The generated texturized meshes of the 3D virtual models were interpreted with Cloud Compare software to measure the orientation of layering and fractures. The structural analyses of this ~50 m diameter impact crater formed within sandstones will provide important clues to better understand the impact cratering process of simple craters in sandstone targets. The crater is particularly important, representing a bridge between experimentally formed impact craters, obtained under controlled impact conditions (MEMIN experiments) (e.g., Kenkmann et al., 2018b) and up to 30 cm in diameter, and larger well-preserved natural simple impact craters of kilometer size (e.g., Meteor crater, Arizona) (e.g., Kieffer, 1971). The crater is key for a better understanding of the impact conditions at secondary crater formation, which is known to play an important role on planetary surfaces.

Acknowledgments

We acknowledge continuous funding by the German Research Foundation, grant KE 732/30-1.

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ID: 123

Abstract Submissions

Topics: Planetary Tectonics & Impact Cratering

Structural analysis of the recently discovered deeply buried complex Jake Seller Draw impact structure in the Bighorn Basin, Wyoming, USA

Sebastian Sturm[1], Thomas Kenkmann[1], Doug Cook[2], Allan Fraser[3], Kent Sundell[4]

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Jake Seller Draw (JSD) is a recently discovered complex impact structure of 4.3 km diameter (Sturm et al., 2024). With 6.5 km of burial, it is the deepest crater ever found. JSD is located in the Bighorn Basin of NW Wyoming, United States (lat 44.11°N / long 108.22° W). It was recognized as a disturbance in two- and three-dimensional seismic profiles. The impact origin could be confirmed by shock effects in quartz crystals obtained from boreholes that show planar deformation features (PDFs) and planar fractures (PFs) (Sturm et al., 2024). Here we present structural characteristics of JSD, based on our interpretation of a two-dimensional East-West seismic profile crossing its center. The 4.3 km diameter of Jake Seller Draw is constrained by inward-dipping normal faults. An elevated crater rim is not preserved. The structure shows a 1-km-wide central uplift and could, therefore, be characterized as a complex impact structure. JSD shows structural characteristics that are similar to other well-known complex impact craters (Kenkmann et al. 2014), including a series of normal faults near the crater rim, partly with listric shapes, that form rotated, down-faulted terrace blocks. Some of these faults merge into low-angle faults toward the center of the crater. However, very deeply seated detachment faults seem to be unconnected to the normal faults. Such detachment faults seem to decouple the displaced crater subsurface from the unaffected basement and imply a minimum depth, measured from the contact with the overlying undeformed strata, of roughly 500 m for the seismic disturbance. The central part of the crater was uplifted. Strata moved inward and upward along several reverse faults. Complex synclines, with widths of around 1200-1500 m, can be detected east and west of the central uplift and are dissected by numerous faults. They show partly half-graben and stair-stepping geometries. The absence of coherent reflectors in the synclines suggests that they are most likely filled with breccia up to 50 m thick. Above the central uplift, we identified a disturbed seismic zone that ranges from the center out to the terraced outer zone. It has no visible layering and could represent chaotic deposition of breccia infill (Sturm et al., 2024). If this interpretation is correct, the deposits may represent resurge deposits, and the impact would have happened a marine or aquatic environment.

Acknowledgments

We acknowledge continuous funding by the German Research Foundation, grant KE 732/30-1.

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ID: 124
Abstract Submissions
Topics: General Tectonics & Regional Studies, Metamorphism & Deformation

Petrological diversity of ultra-high-pressure rocks around the Saidenbach dam (Erzgebirge).

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The Saidenbach reservoir in the Erzgebirge is well known for Variscan ultra-high-pressure (UHP) metamorphic rocks including diamond-bearing felsic rocks and coesite-bearing eclogites. Conditions up to 7 GPa and 1400 °C have been proposed as peak metamorphic conditions for the felsic rocks, but only about 3 GPa and 900 °C for the eclogites. These differences demonstrate the poorly understood relation between the UHP felsic rocks and nearby, as well as regional eclogites. This is further emphasized by the occurrence of the UHP rocks as lenses within high-grade gneisses, in which no evidence for UHP metamorphism has been found yet. Using a combination of optical microscopy, XRF, micro-XRF, and microprobe data, we have systematically studied different rock types from the area around the Saidenbach reservoir including UHP felsic rocks, eclogites, and the adjacent gneisses.

Felsic UHP rocks have been reported in two different variants. The more prominent, coarse-grained type was first described about 25 years ago and has since been the subject of several studies, while another, more fine-grained type has only been recognized recently. Current schemes of their origin invoke large degrees of partial melting at UHP conditions, which is why these rocks have been classified as magmatic. Mineralogical differences between samples are consequently explained by their different whole rock chemistry leading to different crystallization sequences. Most studies, however, have focused on the nature and origin of the diamonds within the felsic rocks while petrological and structural data on the main assemblages is scarce.

All in all, our data is not fully consistent with proposed evidence for a magmatic origin, such as a generally "magmatic texture" or a particular kind of garnet zoning. Although mostly similar to previously described diamond-bearing rocks, our samples show a much larger textural variety, including intensely foliated and banded samples. Garnets in the matrix are characterized by intense reequilibration. Only garnet inclusions in kyanite preserve an earlier metamorphic stage, as shown by their systematically different chemistry. Based on our phase equilibrium calculations, their composition is consistent with formation within the stability field of diamond in excessof 3 GPa. Furthermore, we found new lenses of these diamond-bearing rocks, demonstrating that they occur in a greater area than previously thought.

Eclogites in the area show varying degrees of symplectization that correlate with differences in bulk chemical composition. Despite these differences, all investigated eclogites contain coesite or polycrystalline quartz inclusions that are likely polymorphs after coesite, as well as analogous trends in garnet composition. This argues for a shared metamorphic history, similar to previously proposed pressure-temperatures paths. Most of the host rocks are biotite-bearing high-grade gneisses that show significant migmatization. We find hints at an earlier UHP history, such as monazite exsolutions from apatite, but no conclusive evidence yet.

ID: 125
Abstract Submissions
Topics: General Tectonics & Regional Studies

Regional and structural geology of Neoproterozoic to Lower Cambrian rocks in the Ouansimi copper mine, Western Anti-Atlas of Morocco

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The Ouansimi copper mine in Wawguechrir is located south of the Kerdous inlier in the Western Anti-Atlas in Morocco. Surrounding rocks are overprinted, likely due to the Variscan orogeny, resulting in an anticline formation with internal tectonic elements as folds, normal faults, as well as bend and drag folds, shearing and a thrust fault. The stratigraphic units comprise Neoproterozoic to Lower Cambrian carbonate and siliciclastic rocks which record transgression cycles, interrupted by recurring regression cycles. Furthermore, fossil species as *Stromatolites*, *Calcimicrobes* and *Archaeocyaths* helps to fit the lithologies to the stratigraphy. Veins are mainly NW/SE striking, and host copper mineralization, comprising e.g., chalcopyrite, chalcocite, sulfidic minerals, in combination with carbonates or quartz, as well as copper carbonates at the present-day surface. Vein formation processes, as well as ore formation processes in this area are still not clearly understood. Also, the possible tectonic influence besides the Variscan orogeny is not known yet, but may be linked to the influences of the Atlantic Ocean opening, and hydrothermal events associated with magmatism in the Anti-Atlas. Field observations on the surface and subsurface were implemented which included sampling of the different lithologies, and compass measurements of bedding, faults, fractures, and veins. For petrographic analysis, thin sections for transmitted and reflected light microscopy were prepared. Structural, stratigraphic, and lithological data were combined to compile a geological map, a cross-section, and lithological columns of the area. This study aims to understand the evolution of the depositional system as well as the possible tectonic influence on the formation of faults and veins, as well as folds, beside the Variscan orogeny.

ID: 126
Abstract Submissions
Topics: Modelling Deformation from the Micro- to the Mega-Scale, Geodynamics & Plate Tectonics

Restoration and improvement of cross-sections of the Osning Fault System in northern Germany

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In northern Germany, very little is known about the faults, despite proven neotectonic activity, because many of them are hidden beneath sediments. The Osning Fault System (OFS) in North Rhine-Westphalia is such an active fault system. Major earthquakes occurred at the OFS over the last 400 years. The strongest earthquakes occurred in 1612 and 1767 with an estimated intensity of VI to VII on the MSK scale. Uniquely, the OFS dips to the northeast and rises from basement, while other faults in northern Germany are mostly decoupled from the basement by salt, and dip to the south/south-west. Thus, the OFS is/was destined for glacial isostatic adjustment.

To understand better the evolution of the OL, we carry out 2D retrodeformation using already existing large-scale cross sections along the fault system, based on surface geological maps and sparse drilling information. Using balancing techniques, we verify fault geometries and revise the cross-sections accordingly. We then restore the cross-sections to pre-Cretaceous inversion, to show the original basin geometry.

In the future, we plan to include new, highly detailed seismic profiles to improve the understanding of the past evolution and near-surface expressions of the OFS.

ID: 127
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Preliminary results of paleoseismological trenching along the Feldbiss Fault (Lower Rhine Graben, Germany)

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The Lower Rhine Graben (LRG) is one of the most seismically active regions in Central Europe, characterized by horst-graben structures primarily formed by NW-SE trending normal faults. The LRG is situated within an intraplate tectonic context, forming part of the European Cenozoic Rift System. Seismic hazard assessment in this specific tectonic setting is challenging due to a high anthropogenic impact caused by a dense population and relatively low fault slip rates (approximately < 0.1 mm/yr). Recent tectonic activity has been predominantly observed in the western margin of the LRG. The southwesternmost boundary is marked by the active Feldbiss Fault Zone, which stretches from Aachen, Germany, into the Netherlands with an approximately 60 kilometer length. This fault zone exhibits a series of parallel northeast-dipping normal faults, including the Feldbiss Fault. Previous studies have focused on paleoseismological trenches at the northern section of the Feldbiss Fault Zone. Results from these studies indicate a most recent event in the late Holocene.

We conducted a paleoseismological trenching campaign on the southern tip of the fault zone at the Feldbiss Fault, close to Aachen, to expand our understanding of recent and past fault activity. We combine morphological analysis, shallow geophysics, and paleoseismological trenching, which expose a set of 60 – 85° northeast-dipping normal faults. Stratigraphic units show a cumulative vertical displacement of 1.2 meters. We interpret an occurrence of a minimum of 2 – 3 seismic events, each with a slip per event of approximately 0.1 – 0.6 m. We collected OSL samples from different stratigraphic units to establish a chronology of the interpreted events. The most recent event occurred most likely in the Holocene. Our research enhances a broader understanding of the tectonic activity of the Feldbiss Fault and contributes to lengthening the seismic catalogs.

ID: 128
Abstract Submissions
Topics: General Tectonics & Regional Studies

Geochemical Classification of Thuringian Granites using Multi-Dimensional Scaling

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Recently, granitoid complexes have gained increasing importance and scientific interest. Thereby, particularly important is their potential as a repository for highly radioactive waste and their role in the exploration of deep geothermal potential. Geochemical variations, grain size differences and age are well suited for classifying granites; however also influence their rheological and petro-physical properties. A detailed understanding of these properties is necessary to draw conclusions about the theoretical thermal and hydraulic behavior.

Both, the Mid-German Crystalline Zone (MGCZ) and the Saxo-Thuringian Zone (STZ) are characterized by a various number of granite intrusions during the Carboniferous. These syn- to post-variscan magmatites are part of a complex arrangement with low- to high-grade metamorphic rocks. With approximately 20 “different” intrusive bodies, the classification of the Thuringian granitic rocks suggests a broad variety. Pb-Pb and U-Pb zircon crystallization ages range between 340 Ma and 280 Ma (e.g. Brätz 2000; Zeh et al. 2005; Thieme et al. 2023). However, there is no correlation of these intrusion ages and the intrusion bodies recognizable.

Whole-rock geochemical classification of the granitoids of the MGCZ and the STZ includes the analysis of 80 samples. To visualize differences and to identify similar chemical signatures, multidimensional scaling and clustering of the Kolmogorov-Smirnov similarities was applied in a two-step approach. First, the pairwise Kolmogorov-Smirnov differences (n^2 similarity matrix, n = number of samples) are represented as Euclidean distances using a dimension-reducing algorithm of multidimensional scaling. Second hierarchical and k-mean clustering are applied to the differences. The calculation of the similarity matrix uses the following normalized elements or element ratios: SiO_2, CaO, P_2O_5, Fe_2O_3+TiO_2, MgO, Eu/Eu*, LREE/HREE, V, Co, K/Rb and Sr.

The optimal number of clusters, verified by two methods, resulted in six and five geochemical granitoid types for the MGCZ and the STZ, respectively. These geochemical groups correlate with the petrological-structural description of the samples. Almost all geochemical types occur in almost all "different" intrusive bodies. Considering the crystallization ages with regard to the petrological description and thus to the geochemical types, the literature data correlate with the analytical data.

Based on their geochemical signature, petrological-structural description and age, the granitic rocks of the MGCZ and STZ are interpreted as successive intrusions during melt fractionation with an increasing proportion of middle to upper crust.

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ID: 129

Abstract Submissions

Topics: Mountain Building Processes & Alpine Tectonics

The Alpine cooling history of the eastern Southern Alps

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The NW to N directed indentation of the Adriatic microplate into the European lithospheric domain, initiated in the upper Eocene following the closure of the Piemont-Liguria and Valais oceanic basins, constitutes a key feature of the Neoalpine orogenesis. The separation of the eastern Southern Alps (ESA) along the Giudicarie fault system from the late Oligocene (Middle Miocene at the latest) on and its increased northward push contributes significantly to major tectonic processes in the Eastern Alps north of the ESA: updoming, piggy-back top-N thrusting, and eastward lateral escape of the Tauern Window. The ESA undergo deformation as well, as documented, e.g., by the prominent, dominantly SSE-vergent fold and thrust belt of the Dolomites, as well as the top-WSW directed thrusts of the Dinaric chain and associated flysch sedimentation. New and compiled Apatite (U-Th)/He (AHe) and Fission Track (AFT) data allow the tracing of the exhumation history.

AFT data from the western ESA tend to cluster within consistent Dinaric and Neoalpine distinguishable tectonic blocks. However, the data are quite scattered. AHe data primarily indicate exhumation during the post-15 Ma Valsugana phase, showing a tendency of getting younger towards the east. A smaller number of AHe datapoints document Eocene to Oligocene cooling.

Regional age-elevation profiles of consistent fault-delimited blocks exhibit (i) moderate cooling during the Mesoalpine Penninic subduction, (ii) fast Dinaric exhumation (in the Brixen area), and (iii) fast Valsugana phase exhumation starting at approximately 15 Ma; Notably, this exhumation pulse starts earlier (Chattian/Aquitanian) in the northernmost tectonic block at the NW tip of the ESA.

Time-temperature path modelling confirms the Valsugana phase as the most significant period of tectonic exhumation within the western ESA. According to the modeling, prior to this phase, a significant number of samples remained within the AFT partial annealing zone for an extended period of time, at least from Ladinian times onwards. This is evident in the wide dispersion of single grain ages as well as the AFT length distribution. Nevertheless, fault activity is not excluded during this residence time, as long as it does not result in important heating or cooling of the measured units. Another important finding from the cooling paths is that many samples from sedimentary and magmatic rocks of the Permian and Lower Triassic periods show a complete reset of the AFT system during the Middle Triassic, well before the maximum burial indicated by the stratigraphic record. This high-temperature anomaly could be attributed to the extensive Ladinian volcanism in the study area.

Based on the new thermochronological data, it can be inferred that the Middle Miocene Valsugana phase is the most significant exhumation phase in the ESA. Additionally, this phase begins earlier in the north than in the south. It is essential to consider the complex thermal history of the ESA and the possible long residence time of samples within the partial annealing zone prior to the Neoalpine exhumation when interpreting new data.

ID: 130

Abstract Submissions

Topics: Seismo-Tectonics & Fluid-Rock Interaction, Modelling Deformation from the Micro- to the Mega-Scale

Modeling of earthquakes in extensional tectonics

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Earthquakes occurring on continental normal faults rarely surpass a magnitude of 7.0 Mw. Despite their limited magnitude, these seismic events can cause significant destruction due to their proximity to densely populated areas. Our understanding of the deformation patterns and mechanisms influencing the magnitude of these events is hindered by factors such as long recurrence times, relatively small deformations, and limited observations. In this study, we address this challenge by employing 2D thermomechanical modeling of normal fault seismic cycles.

We use the 2020 Samos, Greece Mw7.0 earthquake as a case study, considering it one of the largest and most thoroughly studied continental normal fault earthquakes. Our modeling approach incorporates visco-elasto-plastic rheology, compressibility, free surface conditions, and a rate-and-state friction law for the fault. The results of the Samos earthquake modeling suggest a pore fluid pressure ratio on the fault ranging from 0 to 0.7.

The model reveals that, during both interseismic and coseismic periods, the majority of deformation occurs not only on the fault but also in the hanging wall and footwall below the seismogenic part of the fault. The most significant vertical surface displacement observed during the earthquake is the subsidence of the hanging wall near the fault, with uplift in the footwall and the remote part of the hanging wall being comparatively smaller.

Furthermore, our modeling of seismic cycles on normal faults with varied setups indicates a dependency of magnitude on the thermal profile and dipping angle of the fault. Low heat flow and a low dipping angle create favorable conditions for the occurrence of larger events, while steep normal faults in areas with high heat flow tend to exhibit smaller magnitudes.

ID: 131
Abstract Submissions
Topics: Viscous Shear, Seismic Faulting & Shock Deformation

Quartz cleavage fracturing and subsequent recrystallization along the damage zone recording fast stress unloading

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Strings of recrystallized grains along cleavage planes in host quartz crystals within pseudotachylyte-bearing breccias from the Silvretta basal thrust, Central European Alps, and within shocked gneisses from the Vredefort impact structure, South Africa, are compared and contrasted. The aim is to obtain the characteristic deformation and stress history during microfabric evolution. Strings of recrystallized grains occur in sets parallel to *r*- and *z*-rhombohedral planes of the host quartz in both localities and along basal planes in Vredefort gneisses. In Silvretta fault rocks, they exclusively occur in quartz clasts within tensional domains associated with the propagating pseudotachylyte-related fault tip, indicating that cleavage occurred simultaneously with pseudotachylyte generation. Cleavage of quartz in Vredefort gneisses is related to shock during impact. Quartz cleavage fracturing along planes of minimum free surface energy is suggested to require fast unloading from high transient stresses, as realized in both geological settings: unloading from >400 MPa within minutes during faulting and from <20 GPa within milliseconds during impact. An additional influence of thermal shock caused by frictional heating is likely. Strain-free grains grew *in situ* along the damage zone surrounding the cleavage fractures at quasi-isostatic stress conditions after deformation and temperatures to allow for static recrystallization of quartz.

ID: 132

Abstract Submissions

Topics: Neo-Tectonics & Tectonic Geomorphology

USAGE OF UAV-BASED PHOTOGRAMMETRY FOR QUANTIFYING THE KINEMATICS OF FIRST-ORDER FAULTS

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Unmanned Aerial Vehicles (UAVs) are versatile tools that have been extensively implemented in geosciences to acquire high-resolution surface data. In structural geology, UAVs have been mainly used to identify and image on outcrop-scale structural discontinuities, notably individual fault planes and fault networks. However, few studies are concerned with identifying fault kinematics and quantifying respective displacement vectors. A 3-D digital surface model (DSM) covering a coastal area of approximately 12 km^2 at Cape Archangelos on the Island of Rhodes, Greece, was generated from UAV-based photogrammetry to scan kilometer-scale fault scarps and a total of 17 Pleistocene marine terraces, which are displaced by these faults. The DSM allows to precisely determine the orientation of the fault planes, which dip steeply and strike mostly towards the NNE. Moreover, the terraces and their cutoff edges were used, respectively, as marker surfaces and marker lines. Based on this information, a workflow was developed to calculate displacement vectors of individual fault segments imaged by the DSM. Overall, the faults are characterized by oblique-normal slip pointing to upper crustal deformation under NE-SW extension. The displacements of older terraces are larger (up to 90 m) than is observed for younger terraces, as well as their strike-slip components. This variation in displacements on individual fault segments may indicate that the faults were active during terrace formation. If so, surface uplift was on the order of 400 m since Pleistocene times, pointing to larger accumulation of displacements of older terraces over time. In addition to UAV photogrammetry, the orientations of principal kinematic axes were inferred from the inversion of outcrop-scale brittle shear faults, measured at locations on or close to the first-order faults. The principal kinematic axes, in general, agree with NE-SW extension inferred from the calculation of displacement vectors for first-order fault segments. This observation supports the notion that the kinematics of small-scale brittle shear faults can be used as proxy for the kinematics of first-order faults. Conclusively, this study demonstrate that UAV-based photogrammetry enhances information of deformed terrains, and its usage can go well beyond imaging structural discontinuities.

ID: 133
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology

Resolving Eo-Alpine kinematics of the Plattengneis Shear Zone (Koralpe, SE Austria) via EBSD & crystalline vorticity axis analyses.

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Mylonites of the Plattengneis Shear Zone preserve a kinematic record of Eo-Alpine tectonism in the Koralm Complex of the Eastern Alps under upper amphibolite to eclogite facies metamorphic conditions (680-700°C and 12-13 kbar). The Plattengneis structural fabric comprises a N-S stretching lineation (L_S), planar foliation (S_1) and an orthorhombic symmetry in the plane parallel to the stretching lineation, indicative of deformation under pure-shear dominated general shear conditions. At present, there is an absence of structures displaying unequivocal kinematics in the published literature and efforts to constrain kinematics from quartz EBSD datasets have yielded ambiguous results. To explore the kinematics, the record of vorticity preserved in the deformation structures of the Plattengneis was investigated at the macro-, micro- and crystal-scales, establishing a series of vorticity axes that describe a complex poly-phase deformation history during the Eo-Alpine tectonism.

Macro- and microscale fabrics in samples of the Plattengneis mylonites (e.g. feldspar σ-clasts and garnet/tourmaline δ-clasts) regularly show a monoclinic symmetry in the E-W section perpendicular to L_S, with a consistent top-west shear sense. A horizontal and N-S striking vorticity axis is estimated for these top-west kinematic indicators. To resolve the vorticity kinematics quantitatively, a crystalline vorticity axis (CVA) method was implemented with EBSD datasets: CVA are computed as rotation axes for the intragranular distortion preserved in individual quartz grains. Computation of all rotation axes and calculation of a bulk axis orientation yielded consistent E-W striking bulk vorticity axes, inclined at an angle of 60-70° westwards for quartz grains. Occurrence of both: (a) the computed N-S striking quartz crystalline vorticity axis (CVA_{qtz}) and (b) the E-W striking σ-clast vorticity axis (VA_{fsp}), is incompatible with a single-phase of pure-shear dominated general shear deformation; triclinic flow symmetries also proved to be incompatible.

Using CPO and misorientation axes of low angle boundaries (LAB) from quartz EBSD data, a model solution involving transposition of multiple vorticity axes during a two-phase deformation is proposed. Under plain-strain pure-shear conditions, CVA_{qtz} is expected to initially develop as an E-W striking horizontal (0° inclination) axis via dominant prism<a> slip in quartz grains during D_1. VA_{fsp} is optimally orientated with a top-W shear sense to provide sufficient rotation of CVA_{qtz} from initially horizontal to the observed 60-70° westward inclination during the second deformation phase (D2). During D_2, a sub-optimal orientation of quartz grains relative to the D_2 stress-field limits the dominance of prism<a> slip. A heterogeneous distribution of LAB misorientation axes indicates the D_2 rotation of CVA_{qtz} imposed by the D_2 stress field occurred via activation of multiple, non-dominant yet mechanically-necessary slip-systems.

Integration of CVA analysis with EBSD crystallographic datasets provided as a critical tool for both revealing and resolving unseen complexities in the deformation and kinematics of shear zone rocks such as the Plattengneis. The crystal-scale kinematic analysis uncovered a poly-phase deformation history and provides crucial evidence for top-west Eo-Alpine kinematics in the Eastern Alps.

ID: 134

Abstract Submissions

Topics: Microstructures, Deformation Mechanisms & Rheology, Mountain Building Processes & Alpine Tectonics

A realistic upper bound of elastic anisotropies in schists and phyllites at the NW margin of the Tauern Window (Eastern Alps, Austria)

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The internal structure of the Alpine orogen is difficult to decipher as structural information is usually limited to surface and seismic data. Seismic results very much depend on the elastic wave velocity model of the rocks. Simple velocity models depend strongly on the rock composition. However, seismic properties are directionally dependent. Anisotropy can be subdivided into intrinsic (crystallographic preferred orientation of minerals/CPO) and extrinsic (shape preferred orientation, compositional layering or fractures) anisotropy. In the investigated rock samples, phyllosilicates and graphite are by far the most important mineral phases for the elastic anisotropy due to their platy shape. Here we present an anisotropy profile (N-S) of phyllosilicate- and graphite-rich samples (mainly Innsbruck quartzphyllite and Bündner schist) from the Brenner Base Tunnel Project in order to obtain a refined velocity model of the north-western Tauern Window.

Phyllosilicate-rich sections with layers of different composition and structure were selected from drill core samples originating from the exploration tunnel. The CPO of phyllosilicates and graphite in 1.5 – 3.5 mm thick cylinders was measured using high energy X-ray diffraction at DESY (Hamburg, Germany) and the ESRF (Grenoble, France). The pole figure data was directly extracted by using single peak evaluation. The CPO of quartz was determined by using electron backscatter diffraction (EBSD). Seismic velocities for each sample were computed using µXRF-based modal composition, single crystal stiffness tensors and the measured CPO. We measured the smallest representative volume element which we consider to be undisturbed by microstructural effects. Therefore, we estimate an upper bound of expected intrinsic velocity anisotropies.

The Vp and dVs anisotropy is variable along the section (Vp anisotropy: 4 – 31 %; max. dVs: 0.2 – 1.1 km/s) with peak values at the transition from the Innsbruck quartzphyllite to the upper Bündner schist. The Innsbruck quartzphyllite displays a slightly higher anisotropy than the Bündner schist. The anisotropy correlates positively with the content and distribution of phyllosilicates and graphite. For example, the presence of 2% graphite can increase anisotropy by 5%. We demonstrate that common minerals of the crust such as feldspar, quartz or calcite can be considered as irrelevant with respect to seismic anisotropies. Microstructures such as crenulation and small-scale folding reduce the anisotropy to an only minor extend.

ID: 135
Abstract Submissions
Topics: Metamorphism & Deformation

Experimental investigation of serpentinite dehydration induced by earthquake-like pressure drops

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Dehydration reactions can influence the occurrence of earthquakes at a range of depths, highlighting the importance of understanding these reactions in the study of seismic activity. We have performed several pilot experiments that included the construction of a controllable fast pressure drop unit attached to the piston-cylinder apparatus. This setup makes it possible to simulate conditions that represent a fast pressure drop during an earthquake event. We focused on serpentinite dehydration because 1/ it plays an important link between the deep geodynamic processes occurring in subduction zones and the seismic and volcanic activity and 2/ the interplay between serpentinite dehydration and deformation during the earthquake cycle is not yet fully understood. To test the experimental setting, we first performed a series of static experiments under the conditions that are already in the olivine stability field. After the static experiments at high pressure (1.1 GPa), we performed the controlled fast pressure drop experiments to 0.3 GPa as well as the ramping experiments, in which a series of pressure build-ups and drops were performed maintaining the high temperatures (570 to 640 °C) to simulate the earthquake cycle. In these experiments, olivine was an order of magnitude more abundant than in the one-hour low-pressure static experiment. The pressure drop occurs in seconds. The ramping experiment lasted only 10 mins before cooling down. The results may challenge conventional wisdom about the timescales of mineral reactions under extreme conditions, such as during earthquakes.

ID: 136
Abstract Submissions
Topics: General Tectonics & Regional Studies

The juxtaposition of the Lausitz and the Erzgebirge during the Variscan orogeny – a tectonic case study of the Elbtalschiefergebirge, Elbe zone

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The Elbe Fault Zone (EFZ) at the northern edge of the Bohemian Massif separates the Variscan massifs of the Lausitz and the Erzgebirge in the NE and the SW respectively. During the Variscan orogeny the Lausitz remained in upper crustal levels whereas the Erzgebirge represents a pervasively deformed nappe complex originated in deeper parts of the orogen. Late Variscan exhumation of the Erzgebirge in combination with dextral strike slip of the steeply inclined Elbe Fault Zone culminated in the juxtaposition of both crystalline complexes with the Elbtalschiefergebirge in between. This fault bounded meta-sedimentary-meta-magmatic unit contains remnants of an early Carboniferous synorogenic basin as well as late Devonian magmatites and marine sediments of the Peri-Gondwana shelf. These very low- to low-grade metamorphic lithologies are heterogeneously deformed and occur as steeply inclined shear lenses.

Based on tectonic field studies and microstructural investigations, here we present a tectonic model featuring a complex shear zone suite. Structurally, the very low-grade lithologies are characterized by isoclinal SW-vergent folds and schistosities dipping moderately steep to the NE. Clasts of the lower Carboniferous debris flow deposits exhibit pervasive NW-SE-oriented, i.e., EFZ parallel stretching lineations. Representing a deeper tectonic level, the Phyllites and associated mylonitic meta-volcanics experienced pervasive deformation during metamorphic peak conditions, asymmetric porphyroclasts display dextral shearing. NE dipping extensional shear zones in the phyllitic unit transect the main foliation and were overprinted by brittle ductile normal faults. Southeast of the phyllitic unit, the Mid Saxon Shear Zone is characterized by strongly deformed gneisses of the Erzgebirge. Affecting the preexisting continuous foliation of the Variscan Erzgebirge nappe complex, Elbezone parallel ductile dextral shearing is evident from various (ultra)mylonitic zones.

We interpret the polyphase tectono-metamorphic evolution of the Elbtalschiefergebirge and the northeastern edge of the Erzgebirge as follows. Two major tectonic phases can be distinguished: i) Initial accretion affected the lithologies of the Elbtalschiefergebirge during NE-SW convergence and caused the pervasive (very) low grade metamorphism. Parallelly, early Carboniferous sediments were deposited in a narrow NW-SE elongated synorogenic basin. ii) The final juxtaposition of the Erzgebirge from deeper crustal levels and the Lausitz occurred during dextral transtension and the formation of the Elbe Fault Zone.

ID: 137

Abstract Submissions

Topics: Mountain Building Processes & Alpine Tectonics

Restoring the nappes of the western Tauern Window using thermochronological and petrological constraints

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How can one structurally restore a cross-section of the Tauern Window (TW) in the European Alps without information about stratigraphy and lateral movement? We use zircon fission-track data (ZFT) and petrological data as temporal and spatial constraints.

Beginning in the late Cretaceous, the Penninic realm was subducted beneath the northern margin of Adria, leading to the collision between Europe (Subpenninic) and the Adria margin (Austroalpine). The resulting Penninic and Subpenninic nappe stack was exhumed by ca. 20 km by the northward push of the Dolomites Indenter (Eastern Southern Alps) in the Miocene. This last deformation stage resulted in synkinematic N-S shortening of the western TW (ca. 70 km), W-E extension and lateral extrusion towards the east.

This study investigates the deformation accommodated by each major tectonic basement unit of the western TW using the following restoration techniques. We kinematically restore the cross-section of [1] along the Brenner Base Tunnel using the software MOVE^{TM} (Petroleum Experts), focusing on the Venediger duplex (VD). We choose area balancing as minimum criteria, because we do not know how much material was transported out of the plane of cross-section by extension and lateral extrusion. We integrate zircon fission-track data (ZFT) as a time-temperature constraint (cooling below ~180°C) and test different geothermal gradients. Petrological data are used to define the maximum depth the VD reached at the time of indentation and as marker for the transition from brittle to viscous conditions of the felsic rocks of the VD (lowest temperature for folding). Starting from today’s cross section, we first displace the entire VD down along the Sub-Tauern Ramp below the 300°C isotherm (brittle to viscous transition of felsic rocks). For this deformation step a geothermal gradient of 50°C/km fits well to the petrological data. Cooling below ZFT annealing zone reveals upright folding of the VD was not possible later than ca. 17 +/- 2 Ma. Subsequent unfolding of the gneiss cores, while conserving surface area, reveals the model to be extended ca. 70 km to the south (i.e. thus equaling indenter shortening), which means that no material left the plane of cross-section by W-E extension or lateral extrusion.

Finally, we reconstruct the hanging-wall nappes above the restored VD, thereby precisely constraining the position of the Austroalpine nappes at that time. The surface samples taken from the Austroalpine nappes must have reached thermal conditions between the annealing zones of apatite fission-tracks and ZFT (115°C and 180°C, respectively) as only the former system was reset in the Miocene. We find that the total thickness of the northern limbs of the Austroalpine nappes and the Penninic nappes together is twice as much after restoration compared to today’s thickness. We postulate that the extension on the Brenner normal fault mainly caused this tectonic thinning, which is approximately 10 km.

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ID: 138
Abstract Submissions
Topics: Applied Structural Geology

Fault rocks and the energy transition: from oil and gas to carbon dioxide storage

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Fault seal analysis is an established workflow in the oil and gas industry. Similar questions have to be addressed when planning and modeling underground carbon dioxide (CO_2) storage projects: will faults in a storage complex leak or seal? Can the injection pressure dissipate into the aquifer or will nearby faults compromise injectivity? While reservoir rocks and top seals can be assessed directly by means of well log analysis and core samples, the evaluation of fault seals dissecting or bounding a potential storage site is much more complicated. This is due to the difficulty of sampling the fault rock, and the 3D complexity of faults and fault zones.

Over the last several decades, joint industry projects have developed fault rock databases that contain mercury injection capillary entry pressure (MICP) measurements on reservoir and fault rock pairs from well core and sometimes outcrop samples. The present study analyses such a database with the goal of providing modeling parameters for CO_2 storage exploration. Most data are from the North Sea region, with reservoir rocks ranging from Rotliegend to Upper Jurassic age.

The database contains present day depth, stratigraphic unit, lithology, clay content, porosity, permeability, and capillary entry pressure, for both the reservoir host rock and a small scale fault in each sample. In addition, the fault rocks are classified as disaggregation zone, cataclasite, phyllosilicate framework fault rock, or phyllosilicate smear, based on backscatter electron microscopy (BSEM).

The parameters have been plotted against each other in varying combinations, applying a variety of filters. Of special interest is the clay content of the host rock, as this is the parameter most readiliy available in exploration. Because the throw of the sampled faults is in the order of a few centimeters only, the clay content of the fault can be assumed to be the same as the host rock, and be used as a proxy for fault rock clay content.

As might be expected, the plots show a positive correlation between clay content and fault rock capillary entry pressures, and a negative correlation between clay content and fault rock permeability. The ratio of change from host to fault rock, however, turned out to be more dependant on deformation mechanism than clay content: although data scatter is substantial, cataclasites have median multipliers very similar to phyllosilicate framework fault rock and even phyllosilicate smears. Only the disaggregation zones have markedly smaller multipliers, which is due to their deformation mechanism of grain rolling, rather than grain crushing. Unfortunately, the database only records present day depth (maximum burial depth), but not depth of deformation.

MICP data can be converted to any fluid system, oil-water, gas-water, or CO_2-water, when appropriate values for interfacial tension and contact angle are used. The fault rock database from decades of hydrocarbon exploration and production is therefore a powerful tool to constrain input parameters for CO_2 storage exploration and injection modeling.

ID: 140
Abstract Submissions
Topics: General Tectonics & Regional Studies, Metamorphism & Deformation

First constraints and geodynamic implicactions of cryogenian metamorphism in the foreland orogenic basement of the southern Dom Feliciano Belt (Uruguay)

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The basement of the Brasiliano-Pan-African orogeny encloses a series of keys to understand the Gondwana assembly, including the timing and conditions of collision between the ancient landmasses. The southernmost part of the Kaoko–Dom Feliciano–Gariep orogenic system is represented in South America by the Dom Feliciano Belt (DFB) consisting of a Schist Belt, a Granite Belt and a foreland basin. At its western side, a series of Archean to Mesoproterozoic rocks compose its foreland orogenic basement, forming part of the Nico Pérez Terrane (NPT). The former represents a crustal block with African affinity located between the colliding Congo and Rio de la Plata cratons, therefore, its metamorphic record holds keys to understand the process of collision between them.

This work presents the first quantitative record of high-grade metamorphism at ca. 660-650 Ma (U-Pb in Titanite, this work) within the NPT. The investigated sample is an amphibolite dominated by garnet, amphibole and clinopyroxene with minor quartz and plagioclase. Orthopyroxene occurs predominantly in reaction textures around garnet, while rutile is observed only as inclusion in garnet. Titanite and ilmenite occur as accessory minerals. The bulk rock composition was used to calculate an isochemical phase diagram between 0.3–1.4 GPa and 700–950 °C. The inferred peak metamorphic assemblage (Grt + Cpx + Amp + Pl + Qz + Rt + Liq ± Ilm ± TTn) is shown to be stable above 1 GPa and ~780 °C. The breakdown of amphibole limits the maximum temperature to ~875 °C. Compositional isopleths were calculated for diagnostic minerals (Grt, Pl, Cpx, Amp, Opx) to further constrain P–T conditions. The isopleth representing the composition of the Ca- and Mg-rich garnet rim ($Mg\#_{25-30}$, Grs_{28-32}), clinopyroxene ($Mg\#_{60-66}$), amphibole ($Mg\#_{50-55}$) and plagioclase cores (An_{39-52}) intersect at conditions of 0.9–1.3 GPa and 800–850 °C, albeit amphibole composition suggests slightly lower pressure conditions compared to other phases. The rutile inclusions in garnet, however, indicate a minimum pressure of ~1.0 GPa. Titanite is only stable at the low temperature end of the indicated P-T area and outside the rutile stability field. The composition of the outermost garnet rim ($Mg\#_{\sim 20}$, Grs_{22-24}) and orthopyroxene ($Mg\#_{40-45}$) intersect at lower pressure and slightly lower temperature conditions of 0.50–0.65 GPa and 760–825 °C. The higher anorthite contents of the plagioclase rims are also consistent with this P-T range, although the measured values are slightly higher than those indicated by the isopleths. The obtained conditions overlap with the stability field of the inferred decompression assemblage of Grt + Amp + Cpx + Opx + Pl + Mg + Ilm + Qz ± Liq. The results presented here reveal P-T conditions comparable to metamorphic records of rocks with similar age located eastwards the DFB comprising both, African and American sides. Consequently, these findings strongly suggest that the basement segments westwards of the DFB, i.e., between the Rio de la Plata and Congo Cratons were part of the main collisional phase of the orogeny, thus discarding alternative models proposing an Ediacaran accretion.

ID: 141
Abstract Submissions
Topics: Mountain Building Processes & Alpine Tectonics

Relationships between sizes of inherited basins and fold-and-thrust belts in crustal-scale analogue models: evolution of the European eastern Southern Alps

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During the Cenozoic evolution of the Alps, the Adriatic plate is traditionally considered as a rigid indenter. The structure of the northernmost part of the Adriatic plate in the eastern Southern Alps of Italy and Slovenia, referred to as European eastern Southern Alps (ESA), however, demonstrates significant internal deformation. Mostly Miocene shortening is accommodated within a WSW-ENE striking, S-vergent fold-and-thrust belt overprinting a pre-existing platform-basin geometry related to Jurassic extension. Jurassic basins show a remarkable bend within eastern Italy and western Slovenia (i.e., Carnic and Julian Alps, respectively), where the N-S striking Belluno basin transitions into the E-W striking Slovenian basin. The influence of this inherited bent and the dimensions of this basin area on Miocene shortening kinematics and geometries is a matter of ongoing debate and the focus of this study.

In this contribution we present a new series of 12 crustal-scale analogue models, addressing the effect of inherited lateral crustal heterogeneities and geometries on the internal deformation of the ESA. The brittle and brittle-ductile analogue experiments include a pre-scribed setup of two basins (areas of lower mechanical strength compared to accompanied platforms) striking parallel to the shortening direction, with the eastern basin being connected to a basin that strikes orthogonal (i.e., northeastern basin). The width of the latter (5 versus 10 cm) is one of the key parameters of this study. Inversion of those basins occurs parallel or oblique to the direction of model contraction. This approach allows us to test the influence of inherited basin widths and geometries on the style and timing of the evolving fold-and-thrust belt.

Our preliminary results support our findings from previous research and show that lateral variations in thrust orientations correlate with areas of lateral strength contrasts (Sieberer et al., 2023). In addition, small northeastern basins are mostly inverted, transported piggy back, and their presence leads to the formation of more faults in eastern model areas, mostly incorporating the eastern platform into the thrust belt. When increasing the size of the northeastern basin, the eastern platform acts more as a barrier compared to models with smaller basins. Setups with pre-scribed small basins mostly result in larger N-S extents of the evolving fold-and-thrust belt in parallel and oblique convergence settings, compared to experiments with larger basins.

To compare analogue modelling results with deformation in the ESA, structural fieldwork along major fault systems within the eastern part of the ESA, east of Lozzo di Cadore, was carried out. From north to south, the Dof-Auda-, Pinedo-Uccea- and Barcis-Staro Selo faults, are overall SSE-vergent, but show changes in strike direction across platform-basin boundaries. In map-view of both, the ESA and oblique shortening experiments, we see a strong impact of the northwestern tip of the eastern (i.e., Friuli) platform on the deformation style of the fold-and-thrust belt.

Sieberer, A.-K., Willingshofer, E., Klotz, T., Ortner, H., Pomella, H., 2023. Inversion of extensional basins parallel and oblique to their boundaries: inferences from analogue models and field observations from the Dolomites Indenter, European eastern Southern Alps. Solid Earth 14, 647-681.

ID: 142
Abstract Submissions
Topics: Planetary Tectonics & Impact Cratering

Shear stresses in experimentally shock-twinned calcite

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Calcite is a ubiquitous mineral at the earth's surface, and ~25% of the currently known 210 impact craters on Earth contain limestone as a prominent target lithology. Thus, calcite has a currently overlooked potential as an indicator for shock deformation. We apply a twin density-based piezometer to shocked calcite formed in an impact cratering experiment, and compare the results with numerically modeled shear stress values.

A 25 cm cube of Carrara Marble was selected as target material. A two-stage light gas gun at the Fraunhofer Ernst-Mach-Institute for High-Speed Dynamics in Freiburg (EMI), Germany was used to accelerate a spherical 2.5 mm iron meteorite projectile to 5 km s^{-1}. A thin section of the crater subsurface was prepared and microstructures were mapped in detail. Foils for TEM inspection were prepared with FIB at the GFZ Potsdam from depths of ~60 µm and ~350 µm below the crater floor.

Multiple line counts of TEM images of the foils were made to determine the twin density. Close to the crater floor, a twin density of 4373±711 twins/mm was measured, while at 350 µm below the crater floor, a twin density of 2893±628 twins/mm was determined. The cratering experiment was numerically modeled using the iSALE-2-D Eulerian shock physics code in the "Chicxulub" version. Principal stresses of the shock wave were recorded during its propagation through the marble. From these, maximum shear stresses were calculated, yielding 942±190 MPa for the sample near the crater floor, and 824±160 MPa at 350 µm below the crater floor.

Twin density and shear stress results of the impact experiment can be compared to calcite twin density-based piezometers e.g. from Rybacki et al. (2013). The impact data points lie well within their margin of error for this piezometer. This shows that an extrapolation of tectonic piezometers to high strain-rate impact deformation is valid. Note that data points from Rybacki et al. (2013) are below ~300 MPa and 800 twins/mm. These stresses are well above the maximum shear stresses of ~125 MPa calculated for dry Carrara marble at the brittle-ductile transition in the Earth's crust (Rybacki et al. 2021). In comparison, peak shear stresses from numerical models of shock waves that occur during the impact cratering process are calculated at 1-2 GPa for shock pressures between 5 and 50 GPa (Rae et al. 2021). Twin densities of several thousand twins/mm are therefore not expected in tectonic settings.

In summary, impact experiments validate and extend calcite twin piezometers originally derived for tectonic processes. High calcite twin densities can thus be used as indicators for high differential stress environments found outside of conventional tectonic situations, i.e. shock metamorphism. Caution should be used as high twin densities are not unique to shock metamorphism and have also been documented in low-strain rate shear experiments (Schuster et al. 2020).

Rae et al. (2021) Icarus, 370, 114687.
Rybacki et al. (2013) Tectonophysics 601, 20–36.
Rybacki, et al. (2021) JGR Solid Earth, 126(12), e2021JB022573.
Schuster et al. (2020) Mineralogy and Petrology, 114(2), 105-118.

ID: 143
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology

Deformation microstructures related to low-angle normal faults of the Rochechouart impact structure, France

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The Rochechouart Impact Structure, France, is a 24 km diameter complex impact crater formed 201 million years ago (Schmieder et al. 2009). This impact structure is hosted within Precambrian to Paleozoic crystalline rocks of Variscan age, found in the northwestern French Massif Central. The crater has been eroded significantly, exposing the target rocks beneath the bottom of the crater fill deposits. Despite extensive erosion, complete sequences of impactites and shock features are visible in the target area. Below the impactites lie quasi-brecciated basement and/or brittlely deformed target host rock, offering valuable insights into understanding the processes of impact-related deformation in the target rock. This study focuses on the characterization of deformational microstructures associated with low-angle normal faults that are formed in crystalline basement rocks of the crater´s ring syncline, situated approximately 3-8 km from the crater center (Kenkmann et al. 2000). We are specifically interested in understanding how strain localization works at elevated strain rates under dynamic loading conditions. Thin sections of rock, sampled from a network of major and subsidiary fault planes were scanned to highlight key areas of interest such as wall rock contacts, comminuted layers, and dark veins. Subsequent analyses of microstructures at these areas were conducted using both a transmitted light microscope (TLM) and scanning electron microscope (SEM). Results from the TLM reveal sequences of grain size variation, sharp and gradational contacts at wall rock, clast-laden dark veins with minor injection, comminution, cataclastic layers with chaotic patterns, and compositional banding. Noteworthy observations include subrounded and angular clasts of quartz and feldspar found in dark veins and cataclastic layers, respectively. The preliminary findings from this study provide insights into the sequence of events that occurred along the fault plane during the crater modification stage. The cataclastic layers, characterized by substantial clasts are indicative of early fracturing and brecciation along the fault plane. As the strain rate increased, comminuted grains emerged, serving as precursors to ultracataclases. The increased surface area, resulting from reduction in grain sizes and a long-normal particle size distribution, may induce preferential frictional melting by eliminating smaller particles. The smooth clast-laden dark veins observed are indicative of incipient melting, potentially acting as a lubricant to reduce interface friction. The analysis of these dark veins in the current study suggests the presence of pseudotachylites, as indicated by preliminary results from the TLM. Nevertheless, additional information from the SEM and TEM studies is necessary for a definitive validation of the assertion. The SEM investigation is essential for a comprehensive validation of the preliminary findings and a deeper understanding of the complex processes at play.

ID: 144
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Topography of the southwestern margins of the Bohemian Massif (Bavarian Forest): the role of Late Cenozoic tectonics

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The Bohemian Massif, along with other Variscan basement units in Central Europe, is thought to have maintained predominantly positive topography throughout the Mesozoic and Cenozoic periods. In old domains such as the Bohemian Massif, present-day topography may arise from a long-term dynamic equilibrium in relief, influenced by rock erodibility, or it may manifest as a consequence of rejuvenation processes driven by climatic shifts or tectonics. This study aims to investigate the topography within the southwestern sector of the Bohemian Massif, specifically the Bavarian Forest, to elucidate the role of Late Cenozoic tectonics on the landscape. Our investigation combines geomorphic and river profile analyses derived from digital topography (Copernicus GLO-30 DEM), including the hypsometric integral, steepness index, Chi (χ) index, and knickpoint distribution along the rivers.

Our results reveal distinct variations in landscape maturity of basement rocks in the Bavarian Forest, showing variations along- and across-strike of the known fault zones. In the Hinterer Bayerischer Wald (Rear Bavarian Forest) to the northeast of the Pfahl Fault Zone, less mature topography is correlated with elevated ridges along the drainage divide between the Danube (which drains into the Black Sea) and the Vltava (which drains into the North Sea). The drainage divide between these two rivers is not in a steady state, showing indications of divide migration. In the Vorderer Bayerischer Wald (Frontal Bavarian Forest), along-strike variations in topography are observed from northwest to southeast. In the northwest, a plateau with a maximum elevation of 740 m potentially results from either uplift of an older peneplain or erosion of less resistant rocks covering the basement rocks. The central segment is relatively more mature, featuring an asymmetric ridge (steeper southwest slope) separating the Danube to the southwest from the Regen (a tributary of the Danube) to the northeast. There are indications of northeastward migration of the drainage divide. The southeastern segment is affected by the pronounced incision of the Danube River and its tributaries into the basement rocks. The distribution of knickpoints in the southeastern part signifies the boundary between extensively incised lower areas and less incised upper areas. Knickpoints along the Pfahl Fault Zone exhibit a distinctive pattern – with abundant knickpoints along S-flowing rivers in the SE section and relatively fewer along N-flowing rivers in the NW section – likely linked to variations in rock erodibility across the fault, vertical displacement on the fault, or alterations in erosion related to the Danube's incision into the basement rocks.

Within the studied scale of the Bavarian Forest (c. 150 km), the climatic conditions are not expected to vary significantly. Additionally, lithology (rock erodibility) appears to exert minimal influence on landscape maturity. This suggests that the relative timing and nature of relative uplift and exposure to erosion are likely responsible for these along-strike variations. Therefore, the uplift in the Alpine Foreland Basin since c. 6 Ma has presumably exerted influence, particularly on the southern regions of the Bohemian Massif, resulting in rejuvenation of topography in the Bavarian Forest, notably within its southeastern segment.

ID: 145
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Theoretical and numerical considerations of faceted topographies at normal faults

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Faceted topographies at normal faults are the perhaps most impressing footprints of active tectonics in geomorphology. Although studied for more than a century, the conditions under which they form and what their properties tell about the tectonic conditions are still not fully understood. Almost perfectly planar triangular facets were found in some settings, but also polygonal facets which are much longer than wide. Since the dip angle of the facets is typically much lower than the dip angle of the fault, it is clear that the facets are not just the exhumed footwall, but have been eroded considerably. In this study, the evolution of faceted topographies at normal faults is investigated theoretically and numerically with the shared stream-power model for fluvial erosion and sediment transport in combination with a recently published extension for hillslopes. As a major theoretical result, it is found that the ratio of the tangent of the facet angle and the dip angle of the fault as well as the ratio of baseline length and horizontal width of perfect triangular facets mainly depends on the ratio of the horizontal rate of displacement and the hillslope erodibility. Numerical simulations reveal that horizontal displacement is crucial for the formation of triangular facets. In turn, facets are rather polygonal and much longer than wide at vertical faults.

ID: 146
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Relation between fault activity and scarp morphology in the Lower Rhine Graben

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The Lower Rhine Graben (LRG) is an area of slow intra-plate extension (~0.1 +/- 0.03mm/yr) in north-western Europe. While the major active faults are well known, the activity of this system as a whole remains poorly understood, mostly because such slow deformation produces weak tectonic signal, easily overprinted by other morphological processes. Indeed, during the Quaternary the LRG has experienced very strong climate changes leading to an alternation of glacial periods characterized by permafrost, braided rivers and aeolian deposits (sand and loess) and of temperate periods with meandering rivers and soil development on the aeolian deposits. In general, the erosion is relatively high in the area. On the same way anthropic perturbations are quite important with large urbanization, strong agricultural practice and mining related subsidence.

We present, for the entire region, a revised and homogeneous fault map, based on morphological observations of fault scarps and offset alluvial terraces realized on a high-resolution Lidar-based DEM. The mapped observations are categorized according to their expression in the landscape also reflecting the certainty of fault location. Then, we compared Lidar information with subsurface trenching data, in order to better constrain the seismic cycles of the LRG faults and the scarp preservation processes. The fault expression in the lidar seems to be related to events clustering, with no clear imprint where the trenches don’t show clustering and allows to assess lateral rupture extension. Moreover, we observed differences between the lidar-based fault map and the mean-slip rates for the LRG composite source model. The areas with the highest slip rates are not necessarily the best preserved. The Lidar DEM shows more lateral variations of the fault expression and activity, and allows to clearly investigate the distribution of the deformation between different faults.

We compiled our active faults model in a database, including several levels of fault mapping (traces, fault sections, faults), with indications about the faults expression and location certainty.

ID: 147
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology, Experimental Rock Mechanics

The Frictional-Viscous Transition in Experimentally Deformed Granitoid Fault Gouge

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Granitoid gouges are the principal non-cohesive fault rock in the continental crust. The frictional-viscous transition in these gouges marks a significant change in strength of the continental crust, constraining the lower limit of the seismogenic zone. Previous laboratory experiments indicated a frictional-viscous transition around 350°C. However, these experiments were limited to short displacements and microscope investigations at 1 µm resolution, hindering a comprehensive understanding of the deformation processes in the ultrafine-grained and rheology dominating gouge.

To overcome these limitations, we conducted a series of experiments on granitoid gouge sheared at constant sliding velocities (*v* = 0.1, 1, 100 µm/s) and to large displacements (~15 mm), followed by systematic microstructural analysis. Deformation temperatures ranged from *T* = 20-650°C, with an effective normal stress and pore fluid pressure kept at 100 MPa. Experiments conducted at *v* = 100 µm/s showed high steady-state shear stresses (66-82 MPa) across all *T* tested. On the contrary, experiments with slower *v* = 1 and 0.1 µm/s showed a progressive decrease in shear stresses at *T* > 450°C, with lowest recorded value being 37 MPa at *T* = 650°C and *v* = 0.1 µm/s. Microstructurally, gouges in fast experiments showed homogeneous cataclastic microstructures being dissected by pervasive intergranular fracture arrays. At elevated *T* and slow *v*, highly localized principal slip zones evolved, where grains were dramaticly reduced to nm-size and tightly packed. Pores substantially decreased in size and were partially filled with newly precipitated minerals (e.g. bt, fds, qtz), indicating the operation of dissolution-precipitation creep.

Our results indicate that at low velocities and large displacements, principal slip zones evolve in which frictional deformation is progressively replaced by dissolution-precipitation creep as temperature increases, defining the frictional-viscous transition in our experiments. Extrapolations of experimental data to construct crustal strength suggest that the frictional-viscous transition may be triggered at temperatures of 180-320°C (or depths of 7-20 km), at slow natural strain rates and in ultrafine-grained fault gouges, due to activation of DPC.

ID: 148
Abstract Submissions
Topics: Planetary Tectonics & Impact Cratering

Fault scaling on the Reykjanes Peninsula (Iceland) as a Mars Analogue: Displacement-length relationship in comparison with Memnonia Fossae, Mars

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Investigating geometric fault properties is essential for reconstructing the geological evolution of a tectonic region. Key parameters such as fault length, dip, and slip provide insights into the mechanical and temporal evolution of the fault systems [1, 2] and how faults accommodate strain and deformation over time. The scarcity of fault scaling studies on extraterrestrial bodies partly due to the limited number of reliable topographic datasets [3], constitutes a notable gap in current studies of planetary structural geology, necessitating additional focused research on fault scaling in extraterrestrial environments. For quantitative analyses of fault geometries on other planets, analogous investigations on Earth are an essential supporting activity. These studies help to interpret remote sensing imagery more reliably by using terrestrial observations to better understand planetary structures.

A previous fault scaling study conducted in the Memnonia Fossae region on Mars yielded valuable insights into geometric characteristics and kinematics of normal faults in this area. Memnonia Fossae is a set of long and narrow grabens radiating outward from the main volcanic region of Mars, Tharsis. We conducted a comprehensive geometric analysis, resulting in the calculation of a maximum displacement vs. length (D_{max}/L) ratio of 0.007 based on measurements taken from 100 individual faults. Normal faults on the Reykjanes peninsula, Iceland [4] were chosen as an analogue to the Memnonia Fossae region of Mars. Both locations share comparable lithologies (i.e., basalts), potentially influenced by dike-induced tectonics. Fieldwork on Reykjanes was conducted in August 2023.

During fieldwork, we got measurements of 74 faults and fractures at 180 waypoints to determine the fault characteristics in this region. Opening, shear sense, throw, and the extension vectors of the faults were recorded in the field. Moreover, for the larger faults, field measurements were supported by measurements gathered from the remote sensing data. Preliminary results show that the D_{max}/L ratio calculated as 0.005. We compare our results to previous measurements of faults on Mars, Earth, and beyond. At the conference, we will present further calculations and discuss them in the context of the comparative structural geology.

Acknowledgment

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ID: 149
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Fault segmentation along the eastern margin of the Upper Rhine Graben by tectonic geomorphology

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The Upper Rhine Graben (URG) is long recognized as one of the most seismically active regions within the interiors of European tectonic plates, characterized by low to moderate seismicity. The eastern boundary of the URG is delineated by the eastern Rhine Graben Boundary fault (eastern RGBF), stretching 300 km from Frankfurt a.M. (Germany) to Basel (Switzerland). Previous investigations in specific sections of the eastern RGBF have identified its distinct geomorphic features, suggesting activity during the Quaternary period. Despite its importance, a comprehensive assessment of segmentation and active tectonics along its entire length has yet to be conducted, neither has the graben interior or basin studied by means of active faulting, segmentation nor seismic hazard by secondary effects like liquefaction. Our study presents a detailed segmentation model for the eastern RGBF and assess the relative tectonic activity of each segment.

To achieve this, we examine the tectonic influence of active faults on the landscape and analyze the morphometric characteristics of the mountain range front and drainage basins along the eastern margin of the URG. Our analysis involves computing morphotectonic indices using Digital Elevation Models (DEMs) from the Shuttle Radar Topographic Mission (SRTM) and airborne LiDAR data. These findings are then integrated with regional geological and seismological data.

Our investigation reveals substantial geometric complexity, predominantly displaying left-lateral kinematics and a marked influence of the extensional phase of the graben on the morphology. Based on geometric and structural fault trace features such as bends, gaps, and changes in strike and the presence and degradation state of tectonic landforms like triangular facets, beheaded channels, and hanging valleys, we identify seven primary structural segments. When considering entire segment rupture and empirical relationships on fault-scaling, the Karlsruhe and Freiburg segments emerge as the most notable, having the potential to generate earthquakes with a magnitude (Mw) around 7.5 ± 0.5. However, this is based only on length-relationships, whereas pre- and historical earthquakes have been observed to paleo-magnitudes well below 7, on the order of M 6.5 ±0.5.

Additionally, based on the tectonic expression in the landscape and the thickest Late Tertiary-Pleistocene deposits, the northern region, encompassing the Odenwald segment, may currently represent a seismic gap due to its very low historical and instrumental seismicity, suggesting potential hazard in the “Heidelberger Loch” area. Furthermore, we assess the long-term slip rate at a key study site within the center of the Karlsruhe segment, using an offset beheaded stream channel and cosmogenic nuclide dating. Our estimation indicates a slip rate of 0.2 ± 0.06 mm/yr over the last 135 ± 10 kyrs. Our paleoseismic and morphotectonic studies introduce the first comprehensive fault segmentation model for the eastern RGBF, offering new insights into active tectonics and establishing a foundation for exploring plausible earthquake rupture scenarios within the URG area.

ID: 150
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology

Tectonic modification of clay mineral alignment in sediments from the Hikurangi accretionary prism (NZ)

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The shortening of sediments in accretionary prisms is accomplished by localized faulting as well as non-localized deformation. While faulting is often easily recognized from seismic sections, accessing the amount and extent of non-localized deformation is rather challenging. In order to address this challenge, we explore samples from the active accretionary prism offshore Gisbourne, NZ at the Hikurangi margin which contains accreted sediments of Pliocene to recent age. Drilling at Site U1318F of IODP Expedition 375 recovered a major accretionary fault, the Papaku Fault, including its hanging wall and footwall. The crystallographic preferred orientation (CPO) of the clay minerals is a measure for their alignment and was determined in 66 sediment samples from the drill core (250-500 mbsf) using high energy X-rays. The results show that the CPO strength of the clay mineral basal planes (00*l*) is in general weak and no depth-related trend can be observed. In the hanging wall of the Papaku Fault, (00*l*) pole figures have non-rotationally symmetric, unimodal density distributions displaying incomplete girdles. In the footwall, most (00*l*) pole figures exhibit unimodal, rotationally symmetric to weak girdle density distributions, with most maxima pointing parallel or subparallel to the drill core axis. Fault zone samples also exhibit rotationally symmetric, unimodal (00*l*) distributions, with maxima perpendicular to the fault plane.

We assume that pre-shortening and pre-faulting, sediments had a weak initial CPO related to sedimentation and compaction with a rotationally symmetric, unimodal (00*l*) distribution. The girdle shape of the distribution in the hangingwall and to a minor extent in the footwall is introduced by non-localized deformation which results in grain-scale folding. Accordingly, diffuse shortening was larger in the present-day hanging wall than in the present-day footwall. Furthermore, we interpret the CPO in the Papaku fault itself to be a result of sediment shearing, overprinting any pre-existing CPO. The position of the Papaku fault is compatible with fault initiation where diffuse shortening was unable to propagate sufficiently towards the foreland.

While our results also confirm existing tectonic models from this part of the Hikurangi margin, more importantly they demonstrate implications for strain distribution in fault and thrust systems as well as the usefulness of clay mineral CPO for unravelling deformation and tectonic processes in accretionary prism sediments.

ID: 151
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

The Paleoseismic Database of Germany and Adjacent Regions PalSeisDB v2.0 - updated and extended

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We present here an updated and extended version of the Paleoseismic Database of Germany and Adjacent Regions - PalSeisDB v2.0. It compiles a summary of previously presented and partly unpublished records of paleoseismic evidence for Germany, including the neighbouring regions in Central Europe within a radius of 300 km, including parts of Austria, Belgium, Switzerland, the Czech Republic, France, Italy, the Netherlands, Poland, and Sweden. This is an extension of the combined historical and instrumental earthquake catalogue which in this area goes back about 1,200 years. This period does not reflect the long seismic cycles in Central Europe, which are expected to be of the order of tens of thousands of years. Therefore, we have developed the paleoseismic database PalSeisDB v1.0, which documents the records of paleoseismic evidence (trenches, soft-sediment deformation, mass movements, etc.) and extends the earthquake record to at least one seismic cycle. It is intended to serve as an important basis for seismic hazard assessment.

The PalSeisDB v1.0 was published in 2020 with detailed documentation. The database itself has been made available via a research data repository. Both publications are available via Open Access. PalSeisDB v1.0 includes paleoseismic evidence at 129 different locations from the literature up to 2016 in the study area. The compilation in PalSeisDB v1.0 showed that only few records of paleoseismic evidence were available for Germany and adjacent regions until 2016. The work clearly demonstrated the effects of past earthquakes and suggested that only a small fraction of this evidence has been found and documented to date.

An update regarding new evidence in the field of paleoseismology and active tectonics as well as an extension of the methodological and technical implementation of the PalSeisDB is mandatory. Since 2016, several new findings of paleoseismic evidence features have been compiled from the current literature within the study area. The results were evaluated and included in the updated version of PalSeisDB (v2.0). In the process, paleoearthquakes have already been identified and assigned to known faults as possible seismogenic sources from the documented paleoseismic evidence. In total, 67 new locations with 103 new paleoseismic evidence records have been added to the PalSeisDB v2.0 since 2016. 21 additional faults have been identified, bringing the total of fault traces associated with paleoseismic evidence to 57. From the documented paleoseismic evidence features a total of 170 paleoearthquakes (105 in v1.0) have been identified in the updated version. The significant increase in the number of geologically documented effects of paleoearthquakes demonstrates the active interest of the scientific community in this topic and thus its scientific relevance.

In PalSeisDB v2.0, further steps are taken to improve the data structure and technical implementation of the database. An extension of the data to historical seismic events with documented environmental earthquake effects (EEEs) and a publicly accessible, web-based map presentation of the data are in progress.

ID: 152

Abstract Submissions

Topics: Microstructures, Deformation Mechanisms & Rheology, Applied Structural Geology

The influence of different clast types on clay mineral alignment in Opalinus clay – first results

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The alignment of clay minerals in shales defines a foliation which controls the anisotropy of some of the rock's properties like permeability, diffusion or mechanical stability. Shale is a potential host rock for the German repository for nuclear waste, hence controls on those properties are important to be understood in greater detail.

The alignment, and hence the anisotropy, is influenced by non-clay particles (further referred to as clasts). The aim of our study is to reveal how different clast types, sizes, shapes, orientations and spatial distribution influence the orientation of clay platelets on the microscale and how this affects the overall alignment.

Our samples originate from a drill core from the shaly facies of the Opalinus clay from the Mont Terri Rock Laboratory (northern Switzerland). Two target layers were chosen which were macroscopically homogeneous and fine-grained, but differ in clast content.

The clay components, mostly kaolinite, illite and chlorite, build up a bedded matrix which contains clasts of quartz, calcite, mica, feldspar and pyrite.

The crystallographic preferred orientation (CPO), i.e. the alignment, of the clay minerals was measured by means of synchrotron diffraction at DESY (Deutsches Elektronen Synchrotron) in Hamburg. The data was analysed using the Mtex Toolbox in Matlab. The alignment strength is quantified from the resulting polefigures by the volume percentage of crystallites within a spherical region. Manually polished sections were studied through SEM with a BSE detector and quantitatively analysed using the software ImageJ.

Our preliminary CPO results show that the alignment strength of the measured clay particles varies from ~13-20%, with an average of 18%. CPO variations within samples apply to all clay mineral types. The variability in alignment is microstructurally analysed with regard to the influence of clasts.

Here, the initial results show that clasts disturb the clay mineral alignment when they fulfil the following conditions: the diameter is larger than the average long axis of the clay minerals and the clast long axis is inclined to the foliation. The size of the disturbed area, measured by the Autocorrelation Function (ACF), depends on the size and shape of the clast. It can be approximated by a rectangular bounding box which has one axis aligned with the foliation, but completely encloses the clast.

The larger scale influence of different clast types and properties on the CPO and related physical properties will be discussed.

ID: 153
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology, Viscous Shear, Seismic Faulting & Shock Deformation

On-fault earthquake energy density partitioning recorded in seismically shocked garnet.

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An earthquake involves the sudden release of elastic energy accumulated during long-term tectonic loading. The released energy is radiated as seismic waves and, mostly, dissipated on-fault by frictional heating (W_H), generation of new grain surface by microfracturing (W_S) and crystal lattice straining associated with dislocation defects (W_{CP}). Quantifying the energy partitioning among these different energy components is fundamental to understand earthquake mechanics. A contribution to this quantification, in addition to seismological, modelling and experimental studies, comes from the study of microstructures of exhumed fault rocks bearing pseudotachylytes (quenched coseismic frictional melts), that preserve the record of thermo-mechanical processes occurring on-fault during earthquake rupture propagation and seismic slip.

We studied a dry, garnet-rich felsic granulite hosting a single-jerk pseudotachylyte vein (3 mm in thickness) from the Woodroffe Thrust (Musgrave Ranges, central Australia). The pseudotachylyte was produced at mid-crustal conditions (500 °C, 500 MPa) during the Petermann orogeny (ca. 540 My). We focused on the cm-sized wall-rock garnet, that is highly fractured in contact with the pseudotachylyte (clast-size down to 20 nm equivalent radius). The clast-size distributions obtained combining EBSD and high-resolution imaging can be approximated to fractal distributions with D-values in the range 1.9–2.3. HR-EBSD (high-angular resolution electron backscattered diffraction) maps show a gradient in residual stresses and GND (geometrically necessary dislocations) density at increasing distance from the pseudotachylyte. The calculated residual stress heterogeneity of 5 GPa and GND density of > 10^{14} m^{-2} in contact with the pseudotachylyte vein decrease to 500 MPa and ~10^{13} m^{-2} in less than 2 mm. High residual stresses are due to dislocations that were produced by the stress pulse at the tip of the propagating earthquake rupture. The absence of fluids in the host rock and the sluggish mobility of dislocations in garnet at the ambient conditions of deformation allowed the survival of the pristine coseismic damage microstructures.

The residual stresses and GND densities measured in contact with the pseudotachylyte are used to calculate a W_{CP} energy density of 0.02 MJ/m^2 by assuming that these measured values are representative for the volume of rock that underwent frictional melting. The same assumption is used to estimate W_S (0.29 MJ/m^2) from the clast-size distributions. These values are compared with W_H (ca. 13 MJ/m^2) estimated from the volume and the mineralogical composition of the pseudotachylyte to provide the complete local, on-fault energy budget of an earthquake. Therefore, most of the energy dissipated on-fault during an earthquake is heat, with subordinate new surface energy and negligible energy due to straining of crystal lattice.

ID: 154
Abstract Submissions
Topics: Mountain Building Processes & Alpine Tectonics, Modelling Deformation from the Micro- to the Mega-Scale

Architecture of Subducted Rifted Continental Margin and Dynamics of Early Collision

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The transition from subduction to collision marks a pivotal geological transformation as tectonic plates cease their subduction, giving rise to intense collisions that reshape landscapes and foster the creation of mountain ranges. We use thermo-mechanical numerical modeling to address the dynamics of continental margin subduction and the subsequent transition to collision.

Several collision orogens, like the Alps, document a typical series of events that are not fully understood:

1. Continental high-pressure (HP) units are formed from the upper crust only during early continental subduction. Hence, only the distal margin is exhumed to great depth. In a mature collision orogen, the continental upper crust is detached from the lower crust at shallow levels, while the lower crust might continue to subduct.

2. These units are rapidly exhumed along the subduction boundary, and their final position in the orogen is “in-sequence,” on top of the continental nappes and below the oceanic suture. Continental HP-units are sandwiched between units that experienced considerably lower peak pressures.

3. Rapid exhumation of HP units is followed by:

3.1. Apparently extensional deformation, of which at least the final stage affects the entire nappe pile.
3.2. A phase of magmatic activity, i.e., the formation of granodioritic and tonalitic intrusions that cut the established nappe pile.
3.3. Rapid rise of topography in the orogen.

The latter two events are often explained by slab breakoff; hence, they indicate the removal of a heavy root and upwelling of asthenospheric mantle. All these events, from the formation of HP assemblages to the intrusion of magma cutting through the established nappe pile, take less than 10 million years.

To investigate this sequence of events and recognize factors controlling their timings and necessary conditions, we reconstruct the transition from subduction to collision with forward modeling. Here, we employ a visco-elasto-plastic modeling approach to model the subduction process followed by collision. The initial setup of the model spans over 2000 km in the horizontal direction, including two continental plates separated by a 700 km long oceanic plate, and is 1000 km deep, including crustal layers, lithospheric mantle, asthenosphere, and lower mantle. To achieve a realistic distribution of temperature and stresses, we introduce an initial distribution of temperature and lithology based on observations.

First, we induce the subduction process of the oceanic plate under the continental plate with converging kinematic boundary conditions. As the subduction slab reaches depth below 300 km depth, we release boundary conditions to let the subduction process continue due to negative buoyancy. As the whole oceanic lithosphere is subducted under the continental lithosphere, the collision of the two continental plates initiates. Finally, the prepared model serves for sensitivity tests to investigate factors controlling the aforementioned events.

ID: 155
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Geological-Geophysical and Sedimentological Analysis of Soil Liquefaction Phenomena along the Kupa River caused by the December 29 Earthquake in 2020, Petrinja (Croatia)

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The tectonically active region of Petrinja/Sisak in central Croatia was hit by a magnitude Mw 6.4 earthquake on December 29, 2020. Alluvial plains of river Kupa hosted several appearances of liquefied material at the surface and lateral spreading features, as well as coseismic surface ruptures, cracks and rockfalls. Liquefaction features such as sand blows were observed in a radius of about 20 km within the epicentral area along the river meanders. The origin of these liquefaction occurrences as well as its context with respect to local morphological features due to river dynamics have been investigated in order to assess future seismic hazards in terms of identifying areas and depths of material highly susceptible to liquefaction. A multidisciplinary approach of geological-geophysical, geotechnical, and sedimentological investigations on- and off-site was performed in a collaborative field investigation of Croatian, French, and German teams in October 2022.

The work presented here focuses mainly on sedimentological aspects deducted from those different investigations. The sedimentological composition was delineated from paleoseismological trenching and coring, for which six short trenches and ten drillings were carried out for different sites, latter ranging between 2 – 10 m in depth below surface. A vertical sediment distribution divided into three main units could be derived for all investigated sites, concordant to the presumed former course of river Kupa. The upper part describes a first unit mainly consisting of silt, clay, and partly sand. The second unit is made of fine- to coarse-grained sand with interbedded clay and silt. The underlying third unit reveals mainly gravel.

Geophysical results, emerging from 2D profiles and areal surveys by Ground Penetrating Radar (GPR) and 2D profiles by Electrical Resistivity Tomography (ERT), highlight the subsurficial distribution of the different soil layers and their geophysical characteristics. Notably, with increasing depth, an increase in electrical resistivity and cone penetration strength was observed. The soil was then categorized according to its susceptibility to liquefy mainly based on geotechnical criteria and their cumulative grain size. Correlated results taken from these different methods suggest the main origin of liquefied ejecta in a depth of 4 – 6 m below surface, hosted by unit two. The overlying first unit, marked by a lower permeability, possibly served as a hydraulic barrier for the water-saturated second unit.

Local river dynamics were derived from drilled, excavated, and sampled alluvial material. Drilled coarse gravel in unit three was found on all sites near the meandering river, pinpointing to a shift of the former riverbed. The overlying drilled alluvium in unit two was caused by deposition processes of the formerly active stream. Therefore, the rivers meandering shape indicates dynamic processes which led to the shift in the course of the river over time. Former flow channels could be determined by the combined presence of finer grained sediments with coarser grains.

To classify the sampled material timewise, dating examinations are ongoing. For an assessment of future seismic hazards, a further correlation of results of different investigation methods has yet to be made.

ID: 156
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology

On the control of quartz crystallographic preferred orientation development

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Quartz crystallographic preferred orientations (CPO) have historically been recognized by means of the c-axis alignment, most easily through a polarization microscope. Since then a wide variety of interpretations have been drawn from c-axis distributions. Despite the common usage, the relation between a finite CPO of a deforming and recrystallizing rock to parameters such as finite strain geometry, recrystallization mechanisms, kinematic vorticity or even deformation temperature are vaguely based on empirical observations.

In order to enlighten the relation between deformation conditions or mechanisms and finite quartz CPOs, we analyze data from different natural and experimental datasets deformed and recrystallized at various P/T-conditions in which bulging or subgrain rotation dominates. We find that the finite c-axis distribution can be decomposed based on simple grain shape parameters, i.e., aspect ratio and long axis direction. In general, in non-coaxial flow the azimuth of the c-axis direction varies systematically as a function of aspect ratio and long axis direction of grains. With increasing strain, c-axes in a recrystallizing aggregate move along a trajectory towards the vorticity axis. Inversely, grains initially oriented with the c-axis parallel to the vorticity axis are those that most efficiently accommodate strain without the need to recrystallize. Independent CPO populations are formed by recrystallized grains displaying (a) long axes approaching the extensional ISA as well as (b) rather low-aspect ratio grains with long axes at a high angle to the foliation. While the former show point to girdle distributions synthetically inclined with the grain shape, the latter exhibit a rotationally symmetric peripheral c-axis maximum.

We interpret the observed relations as being a result of the following processes: (1) change of shape and long axis direction of grains as a function of grain scale deformation by dislocation glide in relation to finite strain, (2) dynamic recrystallization by subgrain rotation resetting grain aspect ratios and contributing to a flow controlled steady-state grain shape fabric and (3) at high driving force conditions, oriented growth of equiaxed grains. While those processes largely operate in parallel, the extend of each contribution depends on several parameters such as the driving forces of grain boundary migration, rate of deformation and grain boundary mobility among others. Many of these processes also depend on temperature. However, it can be demonstrated that any direct correlation made between quartz CPO and deformation temperature is merely the result of a sample set from a limited parameter space. Temperature has not a fist order control on quartz CPO and approaches such as a "c-axis opening-angle thermometer" have therefore to be considered as being wrong. In contrast, if a quartz microstructure has reached steady state, it is possible to qualitatively interpret individual CPO components towards parameters such as driving force (stress as a function of defect densities) and accumulated strain in non-coxial flow.

ID: 157
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

Paleoseismic studies of the estern Rhine Graben Faults (Germany)

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The Upper Rhine Graben situated in Central Europe forms one of the most seismically active intra-plate regions, hosting impactful earthquakes throughout historical periods (e.g., the 1356 Basel earthquake), all below M 7. In recent decades, numerous research studies have been undertaken to characterize the seismic hazard associated with the Rhine Graben, predominantly focusing on the western margins of the graben to uncover Upper Pleistocene-Early Holocene surface rupturing faults. However, previous paleoseismic studies have yielded incomplete estimations of faulting history and seismic potential due to the application of models based on "period and characteristic" fault theories in earthquake geology.

Earthquakes on low slip-rate faults are often not included in historical catalogs due to their infrequent occurrences and extended recurrence intervals, complicating standard seismic hazard assessments. This study presents new fault data from an Active Intraplate Region or Stable Continental Region in Germany, specifically the Upper Rhine Graben rift. The data is derived from seismological, geophysical, and trenching investigations. Holocene surface rupturing events are rare with large recurrence intervals, around 10^3-10^4 years. Associated slip rates are generally well below 0.5 mm/yr, and in some cases, even $\leq$ 0.1 mm/yr. Although secondary earthquake effects are observed more widely, some faults exhibit distinct linear scarps and topographic steps, as revealed by high-resolution DEMs and field surveys.

Our research is geared towards characterizing the seismogenic faults within the Rhine Grabens by examining their neotectonic impact on the landscape and establishing a chronological sequence of seismic events along each fault or fault segment. We conducted geomorphological mapping of faults, analyzed Quaternary deposits, undertook trenching of paleoseismic features, and calculated various morphometric parameters to delineate fault segmentation and account for long-term deformation. Our data supports the kinematics of the faults, enabling us to identify areas with varying levels of tectonic activity.

Paleoseismological studies were conducted at several sites, accompanied by extensive geophysical surveys in the Upper Rhine Grabens:

1. Six trenches were established along and across the secondary topographical fault scarp of the eastern Rhine Graben Boundary Fault north of Ettlingen-Oberweier (Karlsruhe).

2. Three trenches were strategically placed across the Rhine River Fault scarp, intersecting the distal parts of the Neumagen alluvial fan near the village of Tunsel (Freiburg) south of the Kaiserstuhl volcano complex.

Across all study sites, we discovered evidence of surface rupturing earthquakes, offering the initial proof of Late Pleistocene and Holocene tectonic activity with magnitudes exceeding 6. These slow active faults are generally identified by slip rates $\leq$ 0.1 mm/yr, with limited potential to create topographic features in humid/moderate climates. The slip rate of a fault is a crucial parameter governing earthquake occurrence and seismic hazard, as decreasing slip rates extend the average recurrence intervals for earthquakes of a given magnitude. Along with slip rates, also segmentation with more or less active fault strands plays an important role to assess the seismic hazards. As a result, our findings significantly contribute to enhancing the completeness of the earthquake history in the Upper Rhine Graben, but need to be extended to other segments.

ID: 158

Abstract Submissions

Topics: Metamorphism & Deformation

Metamorphic record preserved in ultrahigh-pressure eclogites (Śnieżnik Massif, NE Bohemian Massif)

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The Orlica-Śnieżnik Dome (OSD) is exposed in the Sudetes, forming the northeastern part of the Bohemian Massif. It is interpreted as a fragment of the Moldanubian zone of the Variscan orogen, constituting the Variscan orogenic root. The OSD predominantly comprises orthogneisses alternating with metamorphosed volcano-sedimentary sequences. In the eastern part of the OSD, the Śnieżnik Massif, lenses of high- and ultrahigh-pressure rocks (granulites and eclogites) occur in the orthogneisses. This study focuses on deciphering the metamorphic history of the eclogites from the Śnieżnik Massif.

The studied eclogites exhibit a rather typical metamorphic history for ultrahigh-pressure (UHP) rocks. It consists of UHP metamorphic event followed by isothermal decompression and amphibolite-facies retrogression. The UHP metamorphic event in the studied samples is reconstructed based on the discovery of coesite, which occurs as tiny (~10-20 µm) inclusions present in omphacite and garnet. The well-preserved mineral assemblage associated with the UHP metamorphism comprises garnet + omphacite + phengite + kyanite + rutile + coesite. Conventional geothermobarometry results, based on the Grt-Cpx-Ph-Ky-Coe geothermobarometer, indicate peak metamorphic conditions of ~3.2 GPa at 770°C, consistent with the coesite observation.

The studied samples are characterized by steeply-dipping, subvertical foliation. It is defined by alternating garnet- and omphacite-rich layers and parallel alignment of elongated phengite, kyanite, zoisite/clinozoisite(1) and rutile grains. The mineral assemblage connected to isothermal decompression is present in the form of diopside-amphibole-plagioclase symplectites locally occurring along grain boundaries. The last metamorphic event, characterized by amphibole + plagioclase + zoisite/clinozoisite(2) + margarite, can be observed in the fractures crosscutting the main foliation. This event is connected with retrogression under amphibolite-facies conditions.

ID: 159

Abstract Submissions

Topics: Mountain Building Processes & Alpine Tectonics, Metamorphism & Deformation

Deformation at the base of the Bergell Pluton in the upper Valle dei Ratti (Italy)

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The Bergell Pluton (BP) is a calc-alkaline intrusion located in the Italian Alps, to the northeast of Lake Como and north of the Insubrian Line. It is the second largest among the tertiary intrusions along the Periadriatic Line. The region displays an eastward plunge of axes, exposing both the floor and roof of the pluton. The intrusion continues into the Southern steep belt (SSB), an E-W-striking, north-block-up mylonite zone that affects the pluton and the underlying high-metamorphic nappe pile.

The complex relationship between the BP and the underlying metamorphic rocks was last described by Berger et al. and Davidson et al. in 1996, illustrated in a geological-tectonic map (Berger, 1996). In the upper Valle dei Ratti, a large antiform (VRA) at the base of the BP is exposed, which folds the base of the intrusive rocks and the underlying gneisses into the SSB. We present a new geological map, structural field data and microstructural observations from this area. Petrological mapping reveals an alternating sequence of Bt-rich gneisses and schists adjacent to more leucocratic gneisses below the BP. Metasedimentary and ultramafic rocks also occur at the margins to the Bergell magmatites. Previous maps were inconsistent as despite the recognition of the antiform, the two limbs were displayed as being from two fundamentally different tectonic units below the pluton. We traced metasedimentary layers in the basement, which proves the continuity of a single basement unit. The VRA and associated small-scale folds show E-plunging fold axes and pronounced stretching parallel to fold-axes orientations. This stretching lineation is found in the entire area, also further north in the Val Bodengo and Val Bregaglia (Galli et al., 2013), and is related to top-east shearing. In the study area, it continuously translates into the lineation associated with north-block-up, left-lateral shearing in the SSB. We propose that the mylonitic shear zone of the SSB is folded together with the base of the BP and thus identical to right-lateral, south-block-up shearing at the northern border of the Gruf complex in the Val Bregaglia. This scheme would explain the metamorphic gap on both sides of the Gruf complex and why the SSB does not exist east of the BP.

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ID: 160

Abstract Submissions

Topics: Microstructures, Deformation Mechanisms & Rheology

The crystallographic preferred orientations and structural anisotropies of felsic plutonites – First results of a comprehensive study of German granites

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It is well known from numerous AMS (anisotropy of magnetic susceptibility) studies that felsic plutonites always exhibit anisotropic mineral fabrics. This primary anisotropy is determined by the emplacement mechanisms and crystallisation of the melt. The orientation of late- to post-magmatic structural features, such as extensional fractures, may depend on the pre-existing anisotropic rock body. As granites are considered suitable host rocks for nuclear waste repositories, it is necessary to recognise them as geomaterials that require in-depth structural characterisation. We present the first results of a study covering a large number of oriented pre-, syn- and post-variscan granites from all over Germany at sample scale. A seamless orientation workflow allows direct correlation of all anisotropic features within the geographic reference frame. Primary anisotropy is estimated by analysing the crystallographic preferred orientation (CPO) of the rock-forming minerals using large area electron backscatter diffraction (EBSD) and neutron diffraction. These data are used to calculate intrinsic bulk rock properties, such as Young’s modulus based on the elastic stiffness tensor. Orientation analysis of micro-fractures using a universal stage microscope allows for the characterisation of the post-magmatic fracture network. All granites show weak but clear preferred orientations of the rock-forming minerals. We observe a uniform orthotropic symmetric quartz CPO for granites without significant subsolidus deformation. It is characterised by two point maxima of the positive rhombs with perpendicular girdles and c-axes small circle girdles. This CPO is explained by perpendicular components of axial-rotational distributions around the poles of the positive rhombs with varying intensities. Geographically, the CPOs are coherent at a local scale with mostly subhorizontal alignment of positive rhomb maxima. Annealed microfractures in quartz correlate with the orientation of positive rhombs. Solid-state – high-temperature deformation, even at low strains, leads to a complete overprint of this CPO, e.g. with strong c-axis maxima in Y. First calculations of the whole-rock elasticity reveal that all main phases contribute to a similar geographical alignment of anisotropy while feldspar dominates the whole-rock average. These analyses provide the basis for further correlations, e.g. with the regional tectonic stress fields during intrusion. As the project progresses, AMS measurements and oriented pressure tests will contribute to the comprehensive dataset.

ID: 161
Abstract Submissions
Topics: General Tectonics & Regional Studies

New ideas from old observations: An example from the Leinetal graben

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In the humid and densely vegetated German uplands ("Mittelgebirge"), a detailed understanding of geology and structure is often hindered by the scarcity of exposed rock. The information provided by temporary outcrops is in most cases lost and today even the geological surveys lack the resources to systematically record it. However, publications sometimes yield insights into outcrops long since gone and the opportunity to reinterpret what could be observed there. I report the example of a roadcut created during construction along the A7 motorway north of Göttingen in the 1950s. The motorway cuts across a NW-SE-trending structure that lies within but is highly oblique to the north-trending Leinetal graben. The geology exposed is documented in substantial detail in a paper by Wunderlich (1959), with both slopes of the approximately NE-SW-trending roadcut shown as line drawings. The main feature exposed was an arched, antiformal contact between Lower Jurassic shale above and Middle Triassic lower Muschelkalk limestone below it. Bedding in the Jurassic parallels the contact whereas the Muschelkalk strata beneath form a flexure with dips shallowing from north to south from about 60° northeastward to subhorizontal. All Muschelkalk beds are truncated by the contact. In the south, the south-dipping Jurassic strata are overlain by a small wedge of Muschelkalk and by upper Buntsandstein (Röt) strata which form a tight, NE-verging anticline. This seemingly chaotic arrangement was interpreted by Wunderlich (1959) as the effect of a landslide that had emplaced a jumble of Triassic blocks floating in Jurassic shale over Triassic bedrock. Closer inspection of his drawings reveals a consistent cutoff angle of the Muschelkalk layers truncated by the main contact which cuts stratigraphically downward towards the southwest. This geometry can well be interpreted as the folded footwall of an originally planar, southwest-dipping normal fault which now forms the arched contact. The fault-parallel Lower Jurassic in the hanging-wall suggests a flat segment of the same fault in the Jurassic shale and several hundred meters of normal fault throw. The Muschelkalk and Röt overlying the Jurassic in the south would have been thrust up along the reactivated normal fault where it retained its southward dip and eventually along a newly formed thrust fault splaying from the normal fault where it flattens and then reverses its dip over the folded footwall. The two-stage scenario of initial extension followed by contraction implied by this structural and kinematic interpretation matches very well the regional tectonic evolution. The normal fault probably formed in Late Jurassic to Early Cretaceous time, concomitant with the adjacent extensional Lower Saxony Basin. Folding of the normal fault and its partial reverse reactivation can be confidently ascribed to the well-known Late Cretaceous event of shortening and basin inversion.

Reference:

Wunderlich, H. G. (1959). Tektogenese des Leinetalgrabens und seiner Randschollen. Geologische Rundschau, 46(2), 372-413.

ID: 162
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology

The nature of NW-directed shearing at the bottom of the nappe pile in the Erzgebirge

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We present structural field data, observations form optical microscopy and EBSD data from a 11-kilometer-long section along the upper Pockau valley between Kühnhaide and Pockau (Erzgebirge). From South to North, the section runs from the Reitzenhainer gneiss unit, which belongs to the deepest nappe exposed in the Erzgebirge, structurally upwards into the overlying eclogite-gneiss unit. The section contains the famous Vogeltoffelfelsen location at the top of the Reitzenhainer gneiss unit.

The Reitzenhain gneiss unit consists of various gneisses from dominantly ordovician and potentially cadomian protoliths. The overlying eclogite gneiss unit consists of various, likewise dominantly ordovician protoliths including orthogneisses and metasediments with small occurrences of mafic and ultramafic rocks. At least parts of the eclogite-gneiss unit experienced devonian metamorphism at high-pressure or ultra-high-pressure conditions, while only amphibolite-facies metamorphism is documented in the Reitzenhainer gneiss unit.

Along the section, foliation generally dips dominantly towards NE and the southern end of the section reaches the core of a structural culmination. Stretching lineations trend NW-SE and abundant micro- and macro-structural shear sense indicators denote top-to-the-NW directed motion. In recent papers, formation of the main foliation and top-NW shearing have been attributed to NW-directed, pressure-driven extrusion flow (Poiselle flow) that would have exhumed the eclogite-gneiss unit from great depth.

Deformation in the lower unit is frequently associated with stability of Ti-rich biotite, grain-boundary migration in quartz, and C-axes maxima parallel to the y-direction of finite strain. These observations indicate amphibolite-facies conditions during deformation. Some samples, however, show synkinematic biotite decomposition to chlorite and very fine-grained, recrystallized quartz in shear bands. Still top-NW-directed shearing reaches lower-greenschist-facies conditions and the brittle ductile transition. We investigate if different metamorphic conditions reflect continuous progressive cooling during deformation or two distinct deformation events. The former would not agree with a scenario of an extruding hot channel from great depth in the overlying unit.

ID: 163
Abstract Submissions
Topics: Mountain Building Processes & Alpine Tectonics, Geodynamics & Plate Tectonics

Initial Collision of Gondwana Promontories with Forming Laurasia - The Orogenic Record of Western Pangea in the Devonian

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The supercontinent Pangea resulted from the successive collision of forming Laurasia in the north with the giant Gondwana plate from the south. Although this general scenario is undisputed, the role of the Gondwana plate in Pangean intraplate deformation remains controversial. Especially for Devonian orogenies along various plate boundary zones, numerous models ignore the causal relationship with the Gondwanan collision. Based on the analysis of the spherical strain pattern of the continental crust and the published tectono-metamorphic record, we present here a Devonian plate tectonic scenario for western Pangea and propose that colliding Gondwana is the underlying cause for the orogenies. The former existence of two Gondwana promontories explains the record of: i) the early Variscan / Acadian orogeny in western Europe and North America; ii) the Ellesmerian orogeny of the Greenland-Scandinavian Caledonides; iii) the Antler orogeny in western North America; iv) the tectono-metamorphic record preserved in the Mexican terranes. The Early Devonian collision of the “Armorican spur” of Gondwana with the Midland Micro-Craton of Laurussia initiates early Variscan tectonics on the Gondwanan side, caused the Acadian orogeny of Great Britain and Ireland in a sinistral transpressional regime and initiates post-Caledonian tectonics in Svalbard. Crustal-scale sinistral strike-slip faults, e.g. the Great Glen Fault / Storstrømmen Shear Zone, affect the early Paleozoic Greenland-Scandinavian Caledonides connecting the Gondwana-Laurussia plate boundary zone with the area of the future Ellesmerian fold-and-thrust belt in Arctic Canada and Svalbard. Late Devonian opening of Paleo-Tethys led to plate tectonic reorganization at the Gondwana-Laurussia plate boundary zone. A new collision zone evolved between a promontory to the west of the Armorican spur and the North American sector of Laurussia, initiating prolonged collision into the Permian. Coeval with the ongoing Variscan orogeny in the east, this initial collision in the west caused the lithospheric scale decoupling of North America, initiated sinistral transpressional tectonics during the Antler orogeny and dextral strike-slip tectonics at the western and the eastern margins of North – America, respectively. Deformation at the frontal margin of Laurussia, i.e., present-day Arctic Canada, triggers the Ellesmerian Orogeny. Although the existing Devonian tectono-metamorphic record in the central and southern Appalachians is strongly overprinted by younger tectonics, there is ample sedimentary evidence for widespread collisional tectonics. The occurrence of late Devonian glaciogenic sediments deposited in a subtropical environment coeval with the deposition of the vast Catskill clastic wedge reveals a Himalayan-style uplift-erosion-sedimentation. In summary, the timing and heterogonous tectono-metamorphic overprint are due to the irregular shape of the continental lithosphere of the Gondwana plate resulting in diachronous and localized collision.

ID: 164
Abstract Submissions
Topics: Mountain Building Processes & Alpine Tectonics, Seismo-Tectonics & Fluid-Rock Interaction

Reprocessing of the NRP 20 traverse E1 in eastern Switzerland

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We present first results from reprocessing the reflection-seismic traverse E1 that was acquired in the frame of the Swiss National research Program 20 between 1986 and 1993 and utilized explosives and Vibroseis trucks as sources. Kirchhoff prestack depth migration (KPSDM) was applied and the results were interpreted with the help of geological surface data.

The seismic data set comprised several profile lines from which we started with traverse E1. The traverse is located in eastern Switzerland between Säntisalp in the North and Alpsovrana close to the Italian border in the South. It extends over a length of around 100 km and covers several tectonic domains of the Swiss Alps. From North to South, it transects the allochthonous Helvetic nappe stack, the eastern extensions of the Aar- and Gotthard-massifs, the Northpenninic Bündnerschiefer nappe and finally the Middlepenninic Suretta-nappe with the underlying metamorphic Sub-penninic nappes derived from the Iberian microplate and the distal European margin, respectively.

This study focuses on the reprocessing and reinterpretation of the seismic data. For that, additionally to KPSDM, two advanced depth migration approaches were applied, namely Fresnel Volume migration (FVM) and Coherency migration (CM). The migration was performed in 3D taking into account the true source and receiver coordinate. In contrast to the processing applied previously in the 1980s, the shot gathers were migrated separately and stacked afterwards. The resulting 3D seismic volume has a size of 110 km approximately in North-South and 21 km in East-West direction.

So far, we have reprocessed the explosion seismic data. The migrations show a very sharp south-dipping Moho on the European side as far south as Swiss coordinate 180, further than previous migrations did. Above the Moho lies an up to 5 km thick band of reflectors interpreted as reflective lower crust. A strong discrete reflector is also located at the top of the band. Surprisingly, our initial 3D cube indicates a west-dipping component of the Moho orientation in the northern study area, which is in conflict with regional Moho maps. The Helvetic nappes and most internal Penninic nappes are likewise imaged by a series of well-defined reflectors. Within the external massifs, the brightest reflector follows the Urseren-Garvera zone between the Aar- and Gotthard-massif. It can be traced southward down to a depth of almost 25 kilometers.

These results will be interpreted and compared to the results obtained previously. Currently KPSDM was performed using a constant velocity of 6km/s only. We also performed a first-arrival traveltime tomography and obtained a near-surface P-wave velocity model, which we extrapolated to greater depths. This velocity model will be used for a more reliable depth mapping of reflectors. Other next steps include the addition of vibration seismic data and testing for reflectors below the Moho. Also, we want to address the question whether an Adriatic indenter can be defined in the southern part section E1.

We thank the Swiss Geophysical Commission and Edi Kissling for providing us with the data and support.

ID: 165
Abstract Submissions
Topics: Geodynamics & Plate Tectonics, Planetary Tectonics & Impact Cratering

Variations of Earth's volume driven by intermittend mantle stratification

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Through almost the entire mantle column, oceanic crust is denser than ambient mantle. Near the surface and in a ca. 100 kilometers thick channel below the lower-upper-mantle boundary (LUMB), however, this relation is reversed. At the LUMB the transformation of ringwoodite into perovskite and periclase causes a density increase of more than 5 % in mantle rocks, which makes them denser than crust. 100 kilometers further down a corresponding transformation of garnet in crustal rocks reestablishes the classic density relation. Hence, this density inversion channel constitutes a possible trap for oceanic crust, which would accumulate in the roof of the channel. The consequences of such a layer have been explored in models mainly for Venus, but also in a few studies on Earth's dynamics. A recently published numerical study of convection in Earth's mantle predicts the formation of a crust-rich layer below the LUMB and several recent seismic studies claim to observe large ponds of crust at this depth.

We consider volume changes associated with the formation and destruction of a crust-rich layer below the LUMB. Accumulation of crust would be expected to be continuous, while sequestration into the lower mantle should be episodic due to the metastable nature of the gravitational trap: Once the barrier (the activation energy) is overcome and some crust through the lower phase transition, a run-away downwelling-event would empty the local reservoir. We show that a non-steady-state concentration of crust in the channel would be associated with significant variations in Earths volume easily in the order of millions of cubic kilometers. While transfer of crust from the upper mantle into the channel causes a continuous volume increase (upward return flow of manlte would expand the LUMB), the collapse of crust into the lower mantle would be associated with net volume decrease of more than 5% as the compression of the crust would not be balanced by expansion of the rising mantle rocks. We propose that collapse events could be associated with rising mantle plumes, hence, a net volume decrease of Earth would precede the eruption of large igneous provinces (LIP).

Crustal ponds in the channel are expected and observed in and around oceans. A dramatic regional volume loss in 650 kilometers depth might be able to pull down the surface for a brief time, before "postcollapse rebound flow" would fill the gap and restore the surface. If this would happen in the oceans, the event might be expressed in an outstanding sea-level-drop before the eruption of LIP. This hypothesis is confirmed by a review of eustatic sea-level changes accompanying late Paleozoic – Cenozoic LIPs activity showing that a majority of LIP emplacement are shortly (< 500 kyr) preceded by an episode of up to 50m (average of 25m) eustatic sea-level fall, with return to pre-perturbation levels at the onset of LIP eruption.

ID: 166
Abstract Submissions
Topics: Mountain Building Processes & Alpine Tectonics, Viscous Shear, Seismic Faulting & Shock Deformation

Pseudotachylites along the Pustertal-Gailtal-Line, eastern Periadriatic Fault system, Austria

Muriel Odine Bülhoff[1], Erick Prince[2], Christoph Grützner[2], Kamil Ustaszewski[2]

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Part of the ongoing convergence between Adria and Europe appears to be accommodated by the dextrally transpressive Periadriatic Fault system. The Pustertal-Gailtal Line (PGL) is a segment of this fault system and represents the border between Southern and Eastern Alps. According to recent monitoring, the fault reveals little instrumental and historical seismicity. By investigating pseudotachylite occurrences, we aimed to find evidence for past seismic activity along the PGL. In our study area of c. 19 km^2 to either side of the PGL around Maria Luggau (Austria), we identified cataclasites and fault gouges along the fault core zone. Further analyses were undertaken on sampled cataclastic, foliated Oligocene granitoids as well as garnet-mica schists of the Austroalpine basement.

The macroscale cm- to dm-scale veins containing black fault rocks show optical isotropy under the polarization microscope, testifying to their origin as quenched melts. Some of these veins show an internal foliation. Chemical composition variations of major element concentrations were detected by µ-XRF. Furthermore, sharp margins of mm- to cm-sized injection veins against the surrounding host rock, well-rounded quartz and feldspar clasts, the absence of hydrous minerals in the matrix, as well as spherulites are further hints at a seismogenic origin of the studied fabrics. Although, the internal foliation might suggest overprinting by aseismic creep, the studied fabrics can be identified as pseudotachylites.

ID: 167

Abstract Submissions

Topics: Modelling Deformation from the Micro- to the Mega-Scale, Neo-Tectonics & Tectonic Geomorphology

Multi-Geophysical Imaging of Neotectonic Faults in the Northern Upper Rhine Graben

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As part of the Neotectonics in the Northern Upper Rhine Graben (NeoNORG) project, a comprehensive multi-method geophysical strategy was used to investigate faults within the basin. This study integrates 3D seismic data from the petroleum industry with 2D P-wave and S-wave seismic, Electrical Resistivity Tomography (ERT), and Ground Penetrating Radar (GPR) surveys to create a detailed structural model of two major faults. The 3D seismic data provides resolution of structures between 450 m to 4 km depth, while the 2D P-wave survey, designed for high-resolution, supplemented this data for shallower depths (100-600 metres). The S-wave survey and ERT measurements reveal S-wave velocity contrasts and resistivity differences in the near-surface, enhancing our understanding of the faults up to a few tens of metres. We use GPR to constrain the uppermost, highly conductive, near-surface layers.

We show that both faults have varying dip angles and offset patterns in different stratigraphic units, proving tectonic movement occurred during sedimentation in some layers. In general, the faults both steepen upwards, forming typically listric shapes. They both clearly offset the base Quaternary (by ca. 35m). Finally, the very-near surface methods show that the faults extend up to the Earth’s surface, proving their neotectonic activity.

The study's integrated approach not only aids comprehensively understanding the shallow subsurface, but also underscores the importance of detecting neotectonic fault activity for seismic risk assessment. The methodology adopted in this NeoNORG project serves as a precedent for similar geological investigations, i.e. by exploiting the potential of multi-method geophysical surveys in neotectonic research. It also contributes to our understanding of potential gas migration along fault zones to the Earth’s surface.

ID: 168

Abstract Submissions

Topics: Geodynamics & Plate Tectonics, Neo-Tectonics & Tectonic Geomorphology

Deep crustal earthquakes in northern Germany

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Northern Germany is considered a low-strain intraplate region with low seismicity. Nevertheless, historical catalogues and paleoseismology studies point to earthquakes that are related to major Late Cretaceous reverse faults (Brandes at al. 2015). Much of the recent seismicity in northern Germany exhibits hypocenter depths between 3 and 5 km and is therefore interpreted as an effect of hydrocarbon recovery. However, from 2000 to 2018, seven earthquakes with magnitudes of M_L 1.3-3.1 were detected in northern Germany, at depths of 17.0 to 31.4 km. Because of the deeply located hypocentres and the distance to active gas fields, these earthquakes are most likely natural events. Two of the earthquakes correlate with the Thor Suture. A focal mechanism for one of these earthquakes corresponds to an E-W striking reverse fault and matches the regional geometry of the Thor Suture in this area. Five of the earthquakes are located in the lower crust near the Moho, implying that parts of the lower crust and the crust/mantle boundary in northern Germany act as a structural discontinuity on which deformation localizes (Brandes et al., 2019). The fact that these deep crustal earthquakes occur, together with the presence of faults like the Harz Boundary, the Haldensleben and the Gardelegen faults that reach depths of 20 km and more, underline the possibility of a deep tectonic detachment in northern Germany that might be located near the base of the lower crust. Maybe this detachment played a role in the Late Cretaceous tectonic inversion phase, in which e.g., the Harz Mountains were uplifted (Tanner & Krawczyk, 2017). Numerical simulation suggests that the trigger of the deep earthquakes can be caused by stress change due to glacial isostatic adjustment (GIA). It also implies that earthquakes are possible along optimally-oriented reverse faults, if the GIA stress has not yet been released. Around 15 ka, the Coulomb failure stress (δCFS) became positive for reverse/thrust faults at the locations of four of the deep earthquakes and would consequently allow fault slip along suitably oriented reverse faults, such as the Thor Suture. This is supported by the above-mentioned fault-plane solution that gives evidence for a thrust mechanism.

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ID: 169
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology, Planetary Tectonics & Impact Cratering

Neotectonic movements in Claritas Rupes region on Mars

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Over time, the endogenic activity of Mars has focussed on two large volcano-tectonic centers, Tharsis and Elysium. Specifically, the formation of Tharsis, the largest volcanic province on Mars, affected a significant part of the equatorial western hemisphere of the planet, and the associated stresses caused various sets of tectonic structures. Although the amount and quality of Martian data have strongly improved in the last decade, surface evidence for very recent endogenic activity in Tharsis is sparse. Valuable insight into the interior dynamics of Mars has been provided by NASA Insight's seismometer, revealing current seismicity in the Cerberus Fossae region. However, due to the size of the Martian core and its shadow the detection of distant seismic events in Tharsis remains difficult. Therefore, evidence of very recent volcano-tectonic activity and the dynamics of endogenic processes in Tharsis may only come from remotely sensed data.

Using the images of the Context Camera (CTX) and High Resolution Imaging Science Experiment (HiRISE) that are well suited for the identification of very small-scale surface features, we discovered fresh-appearing scarps in the Claritas Rupes region that are spatially associated with local subsidence centers occurring along the main bounding fault of a major extensional structure termed Thaumasia Graben. Our observations were supplemented by topographic data produced using CTX stereo-pairs which reveal the uphill-facing character of the identified scarps. These newly identified scarps show a clear spatial relationship with recent rockfalls, allowing us to constrain their relative emplacement age. We found that boulders moving downslope of Claritas Rupes are stopped at, and accumulated along, fresh-looking uphill scarps. In addition to rockfalls, the fault emplacement on the western scarp of the southern subsidence zone postdates the formation of SW-NE-aligned aeolian bedforms, based on cross-cutting relationships. In all these cases, the emplacement of these scarps is interpreted as surface expression of very recent tectonic activity attributed to faulting. Therefore, we assert that the described faults may constitute evidence for recent neotectonic activity on Mars.

The discovery of pristine-looking scarps attributed to faulting and their stratigraphic relationships with present-day surface processes and deposits such as rockfalls and aeolian structures indicate a very young age of the fault emplacement. Our observations document that some internal dynamics at Claritas Rupes plausibly remained active in the Late Amazonian or may be even active today.

ID: 170
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology

Fracture corridors in crystalline rock and implications for geothermal resources

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Fracture corridors are tabular zones of significantly-increased fracture intensity, with the fractures commonly being joints. They are common in a range of sedimentary and crystalline rocks, and can be significant conduits for fluid flow in the sub-surface. Although fracture corridors tend to be explained in terms of damage around faults or in terms of mechanical differences between layers, this does not explain why the joints are so closely-spaced, and examples occur in mechanically homogeneous rocks that show no evidence of shearing or nearby faults.

Examples of fracture corridors in crystalline rocks are presented, including from the Lower Palaeozoic metasedimentary and igneous rocks of the Bergen area, which are not related to exposed faults and occur in rock masses that appear to be mechanically homogeneous. A model is presented for their development that involves: (1) a zone of micro-cracks develops in rock; (2) one of the micro-crack propagates until it is connected to a source of mineralising fluid; (3) the fracture is mineralised to become a chloritoid-filled microvein, with a higher tensile strength than the micro-cracked host rock; (4) another micro-crack propagates and the cycle is repeated; (5) the veins are partly weathered out, producing a fracture corridor that appears to consist of joints. This model is not intended to explain all fracture corridors, but it shows that veins within the fracture corridor should be identified and their role considered.

The significance of fracture corridors for geothermal exploration is discussed. It is suggested that fracture corridors can be key features of the background levels of fracturing in the rock mass outside of fault damage zones. Predictions about sub-surface geology means that wells can be planned that have the highest likelihood of intersecting fracture corridors.

ID: 171
Abstract Submissions
Topics: Experimental Rock Mechanics

Precursory Deformation and Earthquake Nucleation – Laboratory Results

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The quest for observable earthquake precursors has stimulated a pursuit lasting for several decades by now. Classical earthquake nucleation models resting on fracture mechanics and/or frictional theory predict that dynamic rupture is initiated by a slow and largely aseismic phase of slow slip. Other models suggest that runup to failure is caused by a cascade of foreshocks ultimately followed by a mainshock. Geodetic and seismological observations of precursory deformation and foreshocks prior to large earthquakes are still controversially discussed. However, in recent years a series of laboratory studies have illuminated some factors and processes affecting the preparation and nucleation of dynamic rupture events. Here we report on laboratory experiments performed at confining pressures of 30 -150 MPa on intact and faulted samples with different roughness, rock types (granite, sandstone, shale) and varying boundary conditions (loading rate, geometry, fault prestress and fluid pressure). Precursory deformation approaching failure is mainly affected by loading conditions (displacement-driven shear vs injection-driven shear), fault roughness, effective normal stress and load point velocity. For all faults, we observe that enhanced loading/injection rates promote unstable stick-slip events. Rough (heterogeneous) faults exhibit extended precursory slip and interplay of small-scale high frequency acoustic emission events and slow confined ruptures during run-up to system-wide slip events. Smooth faults with polished surfaces typically display short preparatory slip that is mostly aseismic. Slip events occur abruptly and are initiated by few large acoustic events. Typical signatures derived from high-frequency monitoring of picoseismic events include space-time changes in b-values, spatial correlation of events (c-, d-values), changes in focal mechanism orientation patterns, seismic moment release and partitioning between seismic and aseismic deformation. These proxies allow separating stable deformation phases from run-up to unstable failure. However seismic deformation only represents a small fraction of total shear strain in laboratory faults and seismic coupling varies during loading. Finally, localization of deformation in slip patches during the precursory deformation phase affects subsequent rupture and slip.

ID: 172
Abstract Submissions
Topics: Mountain Building Processes & Alpine Tectonics, General Tectonics & Regional Studies

Late Mesozoic to Palaeogene cooling history of the Thuringian Forest basement high and its southern periphery (Central Germany) revealed by fission-track dating

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We present new results from a fission track (FT) dating approach on zircon and apatite from the Thuringian Forest, a prominent fault-bounded basement high in central Germany, and its southwestern periphery exposing Mesozoic strata. Samples were collected from exposures of igneous rocks as well as from lower to upper Permian (Rotliegend) continental red beds and volcanics recovered from a borehole southwest of the Thuringian Forest. Apatite FT ages 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 Upper Palaeozoic to Mesozoic rocks. No change in apatite FT ages was detected across the regional-scale Franconian Fault system at the southwestern margin of the Thuringian Forest. Additionally, apatite FT ages of borehole samples southwest of the Thuringian Forest from depths between 9.6 and 2.7 km range from 57 to 18 Ma, suggesting post-Late Cretaceous cooling of this peripheral region. Our data hence support recent models of a continued large-scale domal uplift of Central Germany without verifiable or detectable involvement of individual faults.

ID: 173
Abstract Submissions
Topics: Mountain Building Processes & Alpine Tectonics

A fresh look at mountain-building from the Alpine perspective

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For more than a century, the Alpine-Himalayan chain has served as a crucible for ideas on how Earth's inner workings give rise to mountains. In the past decade, the *AlpArray* project has addressed long-standing controversies regarding the nature of continental subduction and the role of the orogenic crust in transmitting motion from the mantle to the surface, and back. *AlpArray* was a European consortium (2015-2019) employing a state-of-the art passive array of >600 land- and sea-floor seismic stations to probe the deep structure of the Alps at high resolution down to the Mantle Transition Zone (MTZ) and beyond. This experiment involved 47 institutions in 17 countries. The German part of *AlpArray*, entitled *Mountain Building in 4-Dimensions* (4DMB), was funded from 2017-2023 as a multidisciplinary DFG priority program (SPP) with a budget of ~10M€. Here, we show how *AlpArray and 4D-MB* are changing our notions of mountain building, with implications beyond the Alps.

Teleseismic V_p tomography reveals that lithospheric slab fragments beneath the Alps have varied shapes and orientations along strike. In the Western Alps, a SE-dipping slab of European lithosphere is largely detached at and below 150 km. Only in the western Central Alps is the slab still attached, possibly reaching down to the MTZ, where it appears connected to subducted remains of Alpine Tethys. In contrast, the slab fragment beneath the Eastern Alps is detached at shallower depths, between the present Moho (55 km) and 150 km. The position of this subvertical to N-dipping fragment does not coincide with major structures in the overlying orgenic crust. SKS directions beneath the Alps suggest that asthenosphere not only flowed passively around the sinking slab fragments, but may have induced the anomalous northward dip of the detached slab segment beneath the Eastern Alps.

The structure of the orogenic lithosphere also differs profoundly along strike of the Alps, as revealed by local earthquake tomography, ambient-noise studies, S-to-P receiver-functions and gravity studies: In the western Central Alps where the slab is still attached, the exhumed retro-wedge of the orogen overrides a wedge of Adriatic lower crust. In the Eastern Alps where the slab has completely detached, exhumation is focused in the orogenic core (Tauern Window) north of and above thickened lower crust of mostly Adriatic origin. The overlying base of the quartz-rich intermediate crust is interpreted as a decoupling horizon that accommodated coeval N-S shortening, orogen-parallel thinning and extrusion of orogenic lithosphere towards the Pannonian Basin in Neogene time.

Based on *AlpArray,* we propose a new conceptual model for Alpine orogenesis involving one, possibly two Neogene slab detachment events in the Eastern Alps (22-18 Ma, < 14 Ma) after slab steepening and partial slab detachment already at 32-28 Ma. This earlier event may have triggered Periadriatic magmatism, as previously proposed. However, Neogene shallow slab detachment(s) involved no magmatism and arguably facilitated crustal fragmentation along the leading edge of indenting upper (Adriatic) plate. This in turn lead to dramatic changes in Neogene thrust-vergence, foreland basin sedimentation and erosional patterns in the Eastern Alps.

ID: 174
Abstract Submissions
Topics: General Tectonics & Regional Studies, Geodynamics & Plate Tectonics

Gibraltar subduction zone is invading the Atlantic

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Subduction initiation is a cornerstone of the Wilson cycle. It marks the turning point in an ocean's lifetime, allowing its lithosphere to be recycled into the mantle. However, formation of new subduction zones in Atlantic-type oceans is challenging, given that it commonly involves the action of an external force, such as the slab pull from a nearby subduction zone, a far-field compression, or the impact of a plume. Notwithstanding, the Atlantic already has two subduction zones, the Lesser Antilles and the Scotia arcs. These subduction zones have been forced from the nearby Pacific subduction zones. The Gibraltar arc is another place where a subduction zone is invading the Atlantic. This corresponds to a direct migration of a subduction zone that developed in the closing Mediterranean Basin. Nevertheless, few authors consider the Gibraltar subduction still active because it has significantly slowed down in the past millions of years. Here, we use new gravity-driven geodynamic models that reproduce the evolution of the Western Mediterranean, show how the Gibraltar arc formed, and test if it is still active. The results suggest that the arc will propagate further into the Atlantic after a period of quiescence. The models also show how a subduction zone starting in a closing ocean (Ligurian Ocean) can migrate into a new opening ocean (Atlantic) through a narrow oceanic corridor. Subduction invasion is likely a common mechanism of subduction initiation in Atlantic-type oceans and a fundamental process in the recent geological evolution of Earth.

ID: 175
Abstract Submissions
Topics: General Tectonics & Regional Studies

Reconstructing the emplacement conditions of the Bažina Maar (CZ) volcanic rocks by investigating the in- and out-of-phase anisotropy of magnetic susceptibility

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Rock magnetic methods are widely used as tools for studying volcanic rocks and to reconstruct their emplacement conditions. The measurement of the anisotropy of magnetic suscepitbility (AMS) is a well known tool to investigate magnetic fabrics in dikes, lava flows and pyroclastic deposits. Previous Kappabridges only measured the in-phase signal (ipAMS), meaning the AMS response which is in phase with the applied magnetic field. The KLY-5A Kappabridge provides an exciting new opportunity to separate the AMS into the ipAMS component and the out-of-phase (opAMS) component, that under certain circumstances lags behind the applied magnetic field. The two most common sources for an opAMS component in igneous rocks are vicous relaxation of superparamagnetic/single domain (titano-)magnetite grains and weak field hysteresis of ferrimagnetic phases like titanomagnetite and pyrrhotite. In this study, two ICDP cores drilled into the effusive and explosive deposists of the Bažina Maar, located in the Czech Republic, were examined using a KLY-5A Kappabridge. The drilled volcanic units are up to 160 m thick in total, and consist of lapilli tuff, effusive (sub-)volcanic rocks which are overlain by unconsolidated, highly weathered lapilli and scoria deposits. Lapilli and (sub-)volcanic rocks are locally overprinted by apatite bearing sequences, possibly of hydrothermal origin. InAMS and opAMS as well as field- and temperature-dependent magnetic susceptibility and corresponding Curie-Temperatures (T_C) were measured for the volcanic units. T_C*s* between 170 – 300 °C suggest a Ti-rich titanomagnetite as the main ferrimagnetic phase, which is supported by polarizing and scanning electron microscopy. Higher T_C*s* between 450 – 580 °C hint at alteration processes like maghemitisation of the titanomagnetite. The ipAMS component for the effusive volcanic rocks reveals a moderate to steeply inclined magnetic foliation, suggesting an upwards flow as emplacement mechanism. This observation confirms previous assuption that the drillcore has penetrated part of the vent. The opAMS component for the effusive volcanic rocks shows a parallel orientation, which could be caused by weak field hysteresis due to the presence of multidomain titanomagnetite. For the explosive lapilli units, the opAMS response is oblique to the ipAMS signal, revealing a magnetic subfabric. Few effisuve volcanic rocks display an opAMS signal with inverted magnetic maximum and minimum principle AMS axes, possibly indicating a change in domain state from multidomain to stable single domain titanomagnetite grains. We are able to show in this study that the ipAMS and opAMS component provide a powerful tool to reconstruct emplacement conditions as well as eruption dynamics of volcanoes and their products and it should therefor be considered as an additional technique to solve volcanological questions.

ID: 176

Abstract Submissions

Topics: General Tectonics & Regional Studies, Applied Structural Geology

Seismic reprocessing and imaging visualize detachment depths and backthrust reflections within the Variscan Eifel Fold-Thrust Belt, Germany

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We introduce new and innovative reprocessed seismic reflection data from DEKORP87-1A, coupled with borehole details from the deep well RWTH-1 and geological field observations. Understanding the geological and structural framework of the fold-thrust front in the Variscan orogen is crucial for practical applications such as geothermal subsurface exploration. To scrutinize the Variscan orogenic structure in the central German Eifel area, we employed the long-range deep-reaching seismic-reflection line DEKORP87-1A, recorded in the late 1980s.

Initial interpretations of time-migrated subsurface images suggested the existence of various shallow and deep-reaching faults associated with the northern Variscan deformation front. Our seismic reprocessing has improved the coherence of the subsurface image, enabling detailed analyses of individual reflections, including their size and dip angles. Fresnel-Volume migration revealed additional significant structural features within the fold-and-thrust belt of the Eifel, such as reflections of the Eupen and Malsbenden backthrusts, along with distinct detachment reflections.

The detachment, stretching approximately 80 km, dips between 8° to 10° in a southeastern direction along the entire length of the DEKORP87-1A line. Reflection features linked to the Tertiary Eifel Volcanic Field are evident at depth beneath the southeastern end of the seismic line. The reprocessed depth-migrated subsurface image of line DEKORP87-1A offers modern and stimulating insights for interpreting Paleozoic subsurface structures beneath the Eifel Mountains, prompting a reassessment of existing surface-subsurface models for the northern Variscan fold-and-thrust belt in the Eifel area.

ID: 177

Abstract Submissions

Topics: Neo-Tectonics & Tectonic Geomorphology

Quantifying the interaction between surface processes and tectonics during mountain building: the Beaumont number

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To first order collisional mountain belts grow by crustal thickening and gain elevated topography through isostatic compensation. Elevated topography is in turn lowered by precipitation-fueled erosion, providing a feedback-loop between surface processes, tectonics, and ultimately climate. Due to the complexity of this feedback, the factors controlling height, width, and longevity in collisional orogens remain debated. Here, we use a tight coupling between a landscape evolution model (FastScape) and a thermo-mechanically coupled mantle-scale tectonic model (Fantom) to investigate mountain belt growth. Based on several end-member models and the new non-dimensional Beaumont number, *Bm*, we provide a quantitative measure of the interaction between surface processes and tectonics, and define three end-member orogen types: Type 1, non-steady state, strength controlled ($Bm > 0.6$); Type 2, flux steady state, strength controlled ($Bm \approx 0.4–0.6$); and Type 3, flux steady state, erosion controlled ($Bm < 0.4$). *Bm* is defined as the ratio between the critical non-dimensional number determining tectonics and the critical non-dimensional number determining surface process efficiency, and can be assessed without complex measurements or assumptions. To quantify the relative importance of surface processes, tectonics, and climate in collisional mountain belts on Earth we apply *Bm* to the Southern Alps of New Zealand (SANZ), Taiwan, Himalaya-Tibet, Tian Shan, Zagros, European Alps, Pyrenees, and Andes. We find that only the SANZ are erosion limited and at flux steady state ($Bm < 0.4$, mountain belt Type 3), Taiwan is likely strength limited and at flux steady state ($Bm \approx 0.4$-0.6, mountain belt Type 2), while the other orogens are strength limited and do not reach flux steady state ($Bm > 0.6$, mountain belt Type 1). We analyse correlations among *Bm* and its constituent parameters and find that the ratio of shortening strain rate over denudational potential, represented by the fluvial erodibility (K_f), determine *Bm*, that fluvial erodibility correlates with strain rate, and that *Bm* correlates with climate represented by the mean annual precipitation. Our analysis suggests that collisional orogens have a natural tendency towards moderate *Bm* values of a strength-limited Type 1 orogen, that are modified by the climatic conditions, determining the tectonic style on Earth.

ID: 178
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology, Experimental Rock Mechanics

Shock deformation and fault processes during earthquakes

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Mature crustal faults include mm-cm thick slip zones embedded in 1-10 m thick fault cores bounded by damage zones up to hundreds of meters thick. During earthquakes, seismic ruptures propagate along slip zones at a few km/s, fed by elastic strain energy stored in the fault zone and wall rocks. Fault rupture allows relative motion ("fault displacement," up to 50-80 m for earthquakes > Mw 9.0) of the fault wall rocks at an average velocity ("fault slip velocity") of ∼1 m/s. At the rupture tip and in the slip zone behind, rupture propagation induces abrupt stress transients (up to GPas), associated with rapid accelerations (thousands of *g*) that result in fault slip velocities of up to 100 m/s for a few ms. In summary, the combination of large dynamic stress transients, and fault slip accelerations and velocities results in shock deformation conditions in the slip zone (*on-fault*) and in the fault core and nearby damage zone (*off-fault*).

On-fault processes include fracturing of rock at the rupture tip and in the slip zone, resulting in grain size reduction and mechanical amorphization. Depending on the presence or absence of fluids (H_2O, CO_2, etc.), mineral assemblage, fault core and damage zone (transient) permeability, rapid (< 100 ms) temperature rise (> 1000°C) may occur. The attainment of high temperatures and the formation of fine-grained reactive fault materials activate a plethora of physical and chemical processes in the slip zone associated with the rapid decrease in fault strength during seismic slip. The latter, depending on fault geometry, loading and boundary conditions, can allow seismic ruptures to propagate from a few centimetres (Mw -6÷-5 earthquakes) to hundreds of kilometres (Mw 8÷9 earthquakes). *Off-fault* seismic processes are associated with large stress transients in the near field, possibly related to wave emission, and involve *in-situ* fracturing and pulverization of rocks and reactivation (dynamic triggering) of minor faults in the damage zone.

Here I will present the effects of coseismic shock deformation in the fault zone based on field geology, laboratory experiments, and microstructural studies. Some of the effects I will discuss include the formation of (1) reaction products in the slip zone associated with shock wave propagation, (2) asymmetric microfracture networks in the first mm from the slip zone, and (3) damage zones hundreds of meters thick consisting of *in-situ* shattered rocks. The formation of reaction and other fault products and the activation of other processes related to shock deformation are associated with a large reduction (> 50%) in fault strength and may contribute to the propagation of seismic rupture. Although in some cases the origin of these fault structures and products remains debated, their analysis may also provide information on the energy budget during seismic faulting, which to date is unknown.

In conclusion, shock deformation, due to the rapid conversion of stored elastic strain energy in wall rocks into other forms of energy, plays a key role in seismic rupture dynamics, the energy budget of an earthquake and shapes the architecture of seismogenic faults.

ID: 179
Abstract Submissions
Topics: Neo-Tectonics & Tectonic Geomorphology

The nowadays stress field changes recorded by 3-D extensometers TM-71 within the Upper Rhine Graben

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The contribution presents the results of 3-D movements of faults monitored by TM-71 extensometers occurring in the Upper Rhine Graben. As a part of the global TecNet network, TM-71gauges are used for regular highly precise monitoring of fault slips along the observed faults. The long-term monitoring was started here in 90s and the extensometers were installed on eastern marginal faults on sites in Darmstadtium congress hall (Darmstadt), in Wattkopf tunnel (Ettlingen), in Loretto railway tunnel (Freiburg) and on western marginal fault on Deidesheim site. The long-term monitoring results show significant irregular accelerations in scale of first millimeters per year throughout the whole monitored period. The detected fault slips are nonlinear in time on all observed sites and are usually affected by short transient periods of accelerations. These accelerations are probably caused by changes in the stress field orientation, which interrupted the action of the normal stress regime commonly present in the NW Alpine Foreland. For a better understanding, the recorded accelerations were furthermore analyzed using standard paleostress analyses. The result of this analysis will be presented.

ID: 180

Abstract Submissions

Topics: Mountain Building Processes & Alpine Tectonics

The Geology of the Suldtal area, with focus on the Stratigraphy and Detrital Geochronology of the Flysch units

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Melanges and broken formations of the Alps have been studied since the 19th century by numerous authors with different backgrounds, each one contributing to the overall knowledge about their dynamic genesis. However, the lack of agreement and their definition leads to confusion and inconsistency. The Suldtal, being a sparsely studied area, contains undiscovered geologic records about the sin-tectonic sedimentation of the early alpine orogeny. To disentangle the sequence of events from the Late Cretaceous to the Paleogene, a structural and stratigraphic approach combined with detrital dating are taken in this project. The centre of attention was drawn onto the Wildflysch Formation in the Suld Valley, located south of Lake Thun. Macroscopic to microscopic observations on geologic relationship and geometries suggest a progressing accretionary wedge from the Late Cretaceous to the Oligocene. The Helvetic and Penninic units from the Cretaceous to Paleocene are proposed to be thrusted and exposed by the accretionary wedge during the Wildflysch formation in the Eocene. These units are most likely olistoliths transported by gravitational mass wasting processes and deposited in the alpine foredeep together with turbiditic deposits of the Taveyannaz and the Stad Formation from the Helvetic ramp. The horizontal and undeformed nature of these contemporary units, suggest that the post-sedimentary tectonic deformation has played only a minor role in the Wildflysch.

ID: 181
Abstract Submissions
Topics: Microstructures, Deformation Mechanisms & Rheology, Experimental Rock Mechanics

Salt rock mechanics in the natural laboratory

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Salt rocks have unique rheological properties that are integral to geological and environmental studies. Understanding the material behaviour and sealing capacity of salt rocks is crucial for various applications, including predicting the evolution of solution-mined caverns and radioactive-waste repositories within salt formations. This review examines the significance of salt rock rheology across different scales, from natural environments to laboratory settings, emphasizing its relevance in multiple scientific disciplines.

Microstructural examinations of Zechstein 2 (Z2) rock salt cores in the northern Netherlands have revealed a mixed rheology and grain-size-dependent variations in strain rates based on correlation of dislocation creep and pressure solution creep to microtectonic features (Urai et al., 2019; Baumann et al., 2022; Barabasch et al., 2023). Applied research focuses on fluid-assisted grain boundary mechanisms, dynamic recrystallization, and pressure solution processes, particularly in relation to cavern operation and post-abandonment stress relaxation (Urai and Spiers, 2007; Urai et al., 2019). Recent studies have demonstrated the ability to measure creep at low-deviatory stress under extreme stable laboratory conditions, highlighting the significance of pressure solution creep in natural systems (Bérest et al., 2019; Gharbi et al., 2020; Bérest et al., 2023). These findings carry significant implications for understanding deep cavern behavior post-abandonment, emphasizing the necessity of continued exploration and analysis in this field.

Though numerous recent studies address the topic (e.g., Adamuszek et al., 2021; Martin-Clave et al., 2021; Schwichtenberg et al., 2022; Linckens et al., 2023), the influence of second-phase impurities on rock salt rheology remains underexplored. This review will analyze existing literature from various disciplines addressing the micro- to dome-scale impact of second-phase lithologies, including numerical simulations at cavern and dome scales (Baumann et al., 2019; Brouard et al., 2019; Bérest et al., in press), and present new findings from laboratory creep tests conducted on natural salt with varying anhydrite content across dislocation creep and pressure solution creep regimes.

The contributions of Janos L. Urai and Pierre Bérest have been instrumental in advancing our understanding of salt deformation, particularly in the context of predicting the long-term evolution of solution-mined caverns. This contribution is dedicated to the memory of these two exceptional individuals and their remarkable research impact.

ID: 182

Abstract Submissions

Topics: Geodynamics & Plate Tectonics, Applied Structural Geology

Deep thermal field in plate tectonics

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The Wilson Cycle creates specific lithospheric configurations characterized by a distinct geophysical configuration. With 3D data-integrated models we show how the upper few km of the Earth'S crust have characteristic thermal fields depending on the setting and discuss the first-order controlling factors for these differences. We find that always the superposed effects of different thermal conductivities, variable contributions of radiogenic heat in response to crustal thickness and composition, and variations in average geothermal gradient in response to the thermal lithosphere thickness are key. Depending on the setting, the distribution of thermal properties leads to -specific 3D thermal fields that in turn control the local rheology and deformation. Rifts can be hot or cold depending on the rifting mode, the amount of stretching and the time since rift initiation. Accordingly, the "thermal anomaly" in the Upper Rhine Graben (Freymark et al. 2017) is almost unrelated to rifting whereas the thermal anomaly in the East African Rift System (Sippel et al., 2017) clearly relates to an impinging mantle plume. Passive margins can be hotter on their oceanic or their continental side depending on the age of the adjacent ocean (Gholamrezaie et al., 2018). Accordingly, the South Atlantic margins are colder oceanward as there an old oceanic lithosphere is present. In contrast in the North Atlantic the younger ocean and the superposed effects of the Iceland plume result in shallow temperatures increasing oceanward (Gómez Dacal, et al., 2023). Orogens always have a hotter crust than their forelands as the topographic effect superposed with thickening of their radiogenic felsic units lead to higher temperatures in the upper 20 km of the crust than at the same depth levels within the adjacent forelands. This hotter orogenic crust explains the lacking deep crustal seismicity in orogens as the Andes (Rodriguez Piceda, et al., 2022) or the Alpine Himalayan Chain (Kumar et al., 2023).

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