TECTONICS STUDIES GROUP

ANNUAL GENERAL MEETING AND RESEARCH IN PROGRESS 2023

THE ROYAL ARMOURIES, LEEDS

ABSTRACT VOLUME

Sponsors: COMET – Geosolutions Leeds – IAG – IGT

	Session	Presenter (*student)	Talk Title
		WEDNESDAY	
08:30			*Registration, coffee and poster setup*
09:00	*Active tectonics and hazards.* ***COMET-sponsored session.*** *Chair: L. Gregory* *Page 5*	**KEYNOTE: Catriona Menzies.** ***Fluid flow and active tectonics***	
09:30		E. Behboudi*	Shallow tectonic stress magnitudes at the Hikurangi subduction margin, New Zealand
09:45		TBC	TBC
10:00		S. Bello	Morphotectonic anatomy and segmentation pattern of the 1983, Mw 6.9 Borah peak earthquake (Idaho, USA)
10:15		N. I. Medhat*	Inclinometer and improved SBAS methods with random forest for landslides and anchor degradation monitoring in Otoyo town, Japan
10:30			*Coffee and posters*
11:00	*Fault zones and fault growth* *Chair: A. Fagereng* *Page 11*	A. Procter/L. Lonergan	Investigating the effect of sediment loading on the growth of a shale-cored anticline, Caspian Sea
11:15		B. Andrews	Spatial and temporal variations in slip rate across extensional fault networks
11:30		B. Holdsworth	Fissure fills and dykes: the geology of near-surface faulting in basement terrains
11:45		L. Wedmore	An active fault database for the Luangwa Rift, Zambia: implications for continental rifting in thick lithosphere
12:00		C. Orlov*	Determining the origin and evolution of tectonic structures on Mars from surface data
12:15			*Lunch and posters*
13:15	*Fractures, fluids and melts* *Chair: T. Torvela* *Page 17*	A. Macente	The evolution of paleo-porosity in basalts: reversing pore-filling mechanisms using X-Ray computed tomography
13:30		S. Masoch*	Interplay between fluid flow and rock deformation in an exhumed hydrothermal fault-vein network
13:45		A. Bistacchi	Fracturing in a mechanical multilayer under extension: natural examples and numerical modelling
14:00		V. Twomey*	Deciphering tectono-magmatic relationships across southeastern Iceland through palaeostress reconstruction from fault/fracture analysis
14:15		G. Amicarelli*	Reliability of automated fracture detection methods from decimeter resolution aerial imagery
14:30			*Coffee and posters*
15:00	*Georesources and applied structural geology* ***Geosolutions sponsored session*** *Chair: S. Piazolo* *Page 23*	**KEYNOTE: Mark Ireland.** ***Why reliable and reproducible structural interpretations are key for future energy projects***	
15:30		F. Robledo*	The impact of fault interpretation strategies on fault patterns
15:45		L. Burrel	Variation of structural style across the Yorkshire Wolds Chalk aquifer: recent findings from field mapping campaigns and seismic interpretation
16:00		R. Butler	Section restoration and the structural setting of the candidate rad-waste repository in the Jura fold-thrust belt, Switzerland
16:15		J. Gale	Natural and engineered fractures in the energy transition: learnings from core, models, and outcrops
16:30			*Poster session with refreshments*

		THURSDAY	
08:30			*Coffee*
09:00	*Strain, rheology and micro-structures* *Chair: A. Macente* *Page 29*	**KEYNOTE: David Wallis.** ***Stress fields of dislocations in quartz from the Karakoram Fault Zone and their role in transient creep of the continental crust***	
09:30		A. McCaig	Strain localisation in oceanic detachment faults: are serpentine and talc weak minerals?
09:45		G. Toffol*	Stresses of seismic rupture propagation preserved in the lattice of faulted garnets
10:00		E. Blereau	Using kyanite to constrain changes in deformation regime and partial melting during metamorphism
10:15		M. Chinello*	The seismic cycle in bituminous dolostones (Central Apennines, Italy)
10:30			*Coffee and posters*
11:00	*Rifting and basin evolution* *Chair: C. Magee* *Page 35*	E. E. Osagiede	Topological characterisation of rift margin fault network, northern North Sea rift system
11:15		M. Carpenter*	Comparing intrarift and border fault structure in the Malawi Rift: Implications for normal fault growth
11:30		S. Brown*	How and when do intraplate basins record deformations? A multiscale approach to Cenozoic deformations of the Paris Basin
11:45		S. Chantraprasert	A pre-rift low-angle shear zone: its origin and influence on rift structure, Central Gulf of Thailand
12:00		M. Froemchen*	How lithospheric thickness and strength variations facilitate the rifting of ancient cratonic lithosphere
12:15		A. Tamas	Using U-Pb calcite geochronology to better constrain basin-bounding fault reactivation, Inner Moray Firth Basin, North Sea
12:30			*Lunch and posters*
13:30			*Tectonics Studies Group AGM*
14:30	*Convergent margins, intra-continental plate deformation and magmatism* *Chair: L. Wedmore* *Page 42*	S. Z. Woodley*	Tectonic shortening structures in western Arabia Terra, Mars
14:45		G. Arienti*	3D structural modelling in the North-Western Alps (Aosta Valley, Italy): a powerful tool for exploring the tectonic evolution of the Alps
15:00		Z.G. Lugoboni*	Post-nappe brittle deformation in the NW Alps: age constraints from 40Ar/39Ar dating of pseudotachylytes
15:15		R. Dunn*	Demonstrating Scandian age seismogenic deformation within the Moine Thrust Zone using in-situ Rb-Sr LA-ICP-MS
15:30			*Coffee*
16:00		T. Mattsson	Melt transport in the Götemar granite pluton
16:15		J. Sears	Plate tectonic implications for a quadrupolar Proterozoic geodynamo
16:30		R. Vernon	Insights into the structure of the Maltese Islands from new geological mapping
16:45		K. Groves/M. Allen	Does the rain or the strain shape the mountain chain?
17:00			*TSG student prizes and close of conference*

POSTERS

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Active tectonics, hazards, and tectonic geomorphology – COMET-sponsored session

1	Daniel Gittins*	Estimating the depth extent of suface rupturing creep events along the Central San Andreas Fault
2	Federico Pietrolungo*	The November 9, 2022, compressional seismic sequence (Mw 5.5)- another piece of information to the 3D seismotectonic fault model of the coastal Marche-Adriatic offshore area (Italy)
3	Laura Gregory	Quantifying Holocene fault slip rates in SW Turkey: results from cosmogenic nuclide analyses on bedrock fault scarps
4	Bex Robertson*	Is there an isotopic signature to co-seismic deformation? An investigation
5	Natalie Forrest*	InSAR time-series of postseismic deformation on dip-slip faults
6	Ake Fagereng	The 155 km long intraplate, post-glacial, Pärvie fault, Sweden: Insights into stress transients triggering large intraplate earthquakes?

Fault zones and fault growth

7	Giulia Lisi*	Post-Messinian tectonics of the Apulian plateau offshore Capo Santa Maria di Leuca (Southern Italy)
8	Phoebe Sleath*	Outcrop observations of thrust fault linkage in a multilayer with abrupt rheological changes
9	Ahmed Alghurabi*	FWI as a tool to predict fault zone properties: Samson Dome, SW Barents Sea
10	Graham Potts	Quantitative relationships between fault kinematics and glacial processes
11	Sam Wimpenny	Evidence for a time-dependent decrease in fault strength

Fractures, fluids and melts

12	Craig Magee	Intrusion-induced forced folds and fractures
13	Emily Madoff*	A structural analysis of the layered Kakortokites within the Ilímaussaq Complex, South Greenland
14	Stefano Casiraghi*	A semi-automatic workflow for structural interpretation of large point-cloud digital outcrop models on complex fractured metamorphic rocks (Aosta Valley, Italy)
15	Francisca Robledo*	The impact of competence contrast on normal fault dip-linkage
16	Daniel Kluvanec (presented by Ken McCaffrey)	Making use of fault orientation in deep learning models applied to 3D seismic data

Georesoures and applied structural geology – GEOSOLUTIONS LEEDS-sponsored session

17	Dan Mircea Tamas	The role and control of impurities in the deformation of salt (Ocnele Mari salt mine, Romania)
18	Isobel Nash*	From large scale to small scale: The tectonic environment and microstructural characteristics of gold-bearing quartz veins at Croagh Patrick, Ireland
19	Joe Connolly*	Partitioning of fluid flow along faults and fractures in the Bristol Channel Basin: implications for low carbon geoscience projects in SW England
20	Craig Magee	Tektonika – a new diamond access journal for structural geology and tectonics

Strain, rheology and microstructures

21	**Auriol Rae**	**Rate-dependent strength and the scaling of impact craters**
22	**Ben Latimer***	**Strain archives of enclaves and its correlation to rheological conditions: a magnetic and petrographic analysis**
23	**Eloise Matthews***	**Structural asymmetry and shock metamorphism as indicators of impact obliquity at the Gosses Bluff impact crater**
24	**Jack McGrath***	**A modelled case for dissolution precipitation in the Southern Alps, New Zealand**
25	**Manon Carpenter***	**Signatures of dissolution-precipitation creep in the mid crust: an example from the Badcall shear zone, NW Scotland**
26	**Stella Johnson***	**Deformation microstructures in quartz of peak-ring granitoids of the Chicxulub impact crater**
27	**Miriana Chinello***	**Mirror-like surfaces in bituminous dolostones (Central Apennines, Italy)**
28	**John Wheeler**	**The use of electron backscatter diffraction in structural geology**

Rifting, basins and sedimentation

29	**Malte Froemchen***	**Basement rheology influenced rift evolution in the North Taranaki Basin, New Zealand**
30	**Oke I. Okwokwo***	**How have thick evaporites affected early sea-floor spreading magnetic anomalies in the Central Red Sea?**
31	**Riccardo Sordi***	**New insights into a Permo-Triassic rift system: a case study from the Utsira High area, northern North Sea**
32	**Billy Andrews**	**The effect of human factors and measurement obliquity when extracting fault data from 3D seismic data.**
33	**Gayle Plenderleith**	**The effect of breached relay ramps on early post-rift sedimentary systems**

Convergent margins, intra-continental plate deformation and magmatism

34	**Giulia Fedrizzi***	**Melt patterns in migmatites: linking numerical experiments and field observations to understand rock-melt mixtures**
35	**Taija Torvela**	**Strain localisation is not primarily controlled by melt fraction in the migmatitic middle crust**
36	**Gamal Ahmed***	**The relationship between thrusting and dyke emplacement: Insight from the Um Gheig thrust belt, Egyptian Nubian Shield (East African Orogen)**
37	**Tobias Mattsson**	**Deciphering laccolith growth with palaeomagnetism**
38	**Jim Sears**	**Proterozoic Supercontinent Nuna in a quadrupolar framework**
39	**JK Ammu**	**Characterizing fracture systems and their connectivity from the frontal exposure of a major thrust: Insights from Ramgarh thrust, Eastern Himalaya, Sikkim**

Active Tectonics, Hazards, and Tectonic Geomorphology

COMET-sponsored session

KEYNOTE PRESENTATION

Fluid flow and active tectonics

[1*]Catriona D. Menzies

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Interactions between fluids and rocks at plate boundaries result in major geochemical changes that help control variations of the composition of the oceans and atmosphere over geological time. Fluid distribution and redistribution exerts controls on the fundamental structure of plate boundaries and the earthquakes that result from movements of those structures. More specifically, fluids modify the chemical and physical properties of fault zones, which may prime them for repeated rupture by the generation of high pore fluid pressures and precipitation of commonly weak, secondary minerals. Fluid flow paths, sources and fluxes, and the permeability evolution of fault zones throughout their seismic cycles remain poorly constrained, despite their importance to understanding fault zone behaviour. Here I present some examples from different active tectonic settings of how geochemical measurements can be integrated with geological, geophysical and material properties data to trace the role fluid play in the evolution active tectonic process. At the Alpine Fault plate boundary in New Zealand, stable and radiogenic isotopes (oxygen, hydrogen, carbon, strontium, helium) enable identification of fluid sources, fluxes, flow paths and fluid-rock interactions revealing that the geometry of the plate boundary focusses meteoric water onto the crustal-scale fault zone. At the Mariana Subduction Zone, the chemistry and isotopic composition of fluids and xenoliths erupted from serpentinite mud volcanoes reveal the control of prograde metamorphic reactions on carbonate mineral stability and mineral-bound water release to the subduction channel, which can be mapped out across the subduction zone.

Shallow Tectonic Stress Magnitudes at the Hikurangi Subduction Margin, New Zealand

[1,2*]Effat Behboudi, [3] David McNamara, [1,2] Ivan Lokmer

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Quantifying tectonic stress magnitudes is crucial in subduction zones for understanding crustal deformation processes, fault geomechanics, and variable slip behaviour on plate interfaces. The central Hikurangi Subduction Margin (HSM), New Zealand is characterized by shallow slow slip events (SSEs) and creeping at the plate interface, which may in part link to tectonic stress within the overriding plate. This study constrains the magnitudes of the *in-situ* stress tensor for the HSM to better understand tectonic regime within the shallow (<3km) HSM forearc. Results reveal effective σ_3: S_v ratios of 0.66±0.2 and effective S_{Hmax}: S_v ratios of 1.03-3.11 within the central HSM. These stress ratios suggest a prevalent thrust to strike-slip (σ_1=S_{Hmax}) faulting regime across the central HSM. Stress magnitudes and recorded ENE-WSW S_{Hmax} orientations in the central HSM suggest a stress regime such that $\sigma_3 \leq S_v$ and ENE-WSW σ_1 = S_{Hmax}, subparallel to the E-W Pacific-Australian plate motion. On the other hand, the analysis of old NNE/NE striking compressional faults in this region indicates a stress regime such that σ_3 = S_v and NW-SE σ_1 = S_{Hmax}. Taking these two observations into account, it is evident that the stress regime in this region has changed over time. The variation of stress state over time, can be explained by a combination of E-W Pacific-Australian forces and the development of upper plate overpressures in the central HSM. High pore pressure (Pp) reduces the effective normal stress and fault shear resistance on the NNE/NE striking compressional faults in the central HSM, allowing the hangingwalls of these faults to slip more easily in response to E-W Pacific-Australian forces and consequently rotate the stress state over time.

TALK CANCELLED

Morphotectonic anatomy and segmentation pattern of the 1983, M_w 6.9 Borah Peak earthquake (Idaho, USA)

[1,2*]Simone Bello

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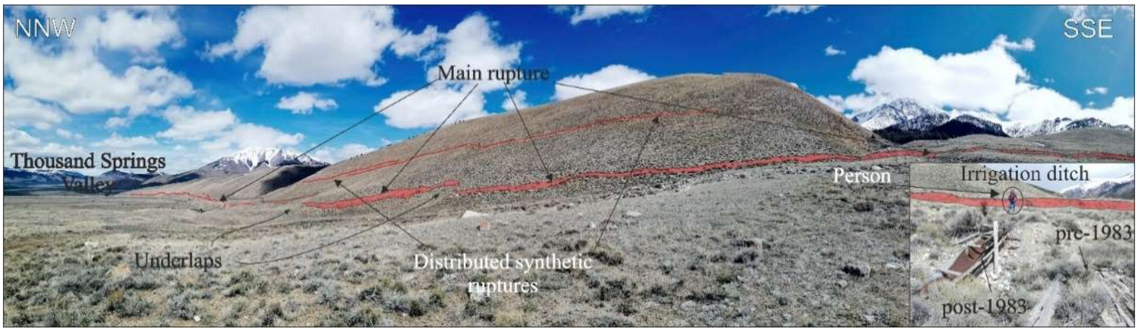
Following survey campaigns along the Lost River Fault (Idaho, USA), we integrate different datasets to obtain a detailed segmentation of the Borah Peak earthquake (1983, M_w 6.9). The latter ruptured with a normal-oblique kinematics producing coseismic ruptures with throw up to 3m. High-Resolution Topography and a large dataset of vertical separation data, combined with rupture zone width (RZW) measurements, new fault/slip data, and an analysis of structural-geometric complexities, highlight a deformation partitioning and a clear multiscale segmentation of the fault, providing new constraints for paleoseismic and seismotectonic studies. In 1983, the two main activated segments had completely different rupture behaviours, with important RZW in the southern portions and with concentrated deformation along the northern portions. The distributed ruptures, in addition to being a large percentage of all deformation in terms of a total length of the ruptures (~19.5 km vs 31 km in total for the main ruptures) also accommodate most of the surface deformation (~66%). We also show that 83% of the deformation in terms of length of the surface faulting is located at the hangingwall of the main rupture, while at the footwall it is located the remaining 17%.

The fault/slip data highlight the control of obliquity and kinematic partitioning in the surface expression of the earthquake propagation. We interpret the coseismic and long-term behavior, showing that the two activated segments had similar cumulated behaviours in distributing the deformation over time, even with different geometries (Bello et al., 2021, 2022).



Bello S. et al. 2021 “High-resolution surface faulting from the 1983 Idaho Lost River Fault Mw 6.9 earthquake and previous events”, Sci Data 8, 68. https://doi.org/10.1038/s41597-021-00838-6

Bello S. et al. 2022 “High-detail fault segmentation: Deep insight into the anatomy of the 1983 Borah Peak earthquake rupture zone (Mw 6.9, Idaho, USA)”, Lithosphere 2022 (1): 8100224. https://doi.org/10.2113/2022/8100224

Inclinometer and Improved SBAS Methods with Random Forest for Landslides and Anchor Degradation Monitoring in Otoyo town, Japan

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Kochi prefecture is one of the active zones in Japan that is frequently subjected to landslides due to heavy precipitation in typhoon seasons. The slow-moving landslides there have been considered not only by responsible persons in the local prefecture but also by those in the National Government of Japan.

We tried to observe the landslide movement at Otoyo town by implementing ground and satellite-based tools. Although the accuracy of the ground-based measurements and the expensive cost to establish the borehole inclinometer survey, there is no previous InSAR study that has been done before at Otoyo town, in addition to the ability of the utilized tools to discriminate between active and inactive slow-moving landslides. Furthermore, the possibility of using satellite-based measurements as a monitoring tool for ground-anchor efficiency with ground-based inclinometer survey as well. There are three types of land cover in the study area; urban, field, and forests, so we chose the Random Forest (RF) model to extract low-coherence pixels using optical and radar satellite sensors to construct the RF important features and precisely remove pixels causing decorrelation.

The comparison between the long-temporal monitoring of ground-based surveys including inclinometer (boreholes) and anchor tension distribution and synthetic radar using Coherence-Based Small Baseline Subset (CB-SBAS) measurements, showed a consistent time-series displacement correlation, being enhanced after introducing the RF mask into the procedure analysis. Our research contributes to mitigating the landslide impacts at Otoyo town and its surroundings.

Fault Zones and Fault Growth

Investigating the effect of sediment loading on the growth of a shale-cored anticline, Caspian Sea

Andrew Procter[1], Daniel T. Roberts[2], Lidia Lonergan *[1] and Stephen Dee[3]

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Here we test the hypothesis that the growth of a shale-cored anticline in the South Caspian Sea Basin has been amplified by the gravitational loading of the weak underlying Maykop Shale Formation. The fold is imaged on three-dimensional seismic data; detailed mapping documents unusual growth-strata geometries that suggest "withdrawal" of shale in the surrounding synclines and inflating of the core of the anticline. We used ELFEN two-dimensional plane-strain finite element code to investigate the mechanics of fold growth. The overburden and syn-kinematic sediments are modelled as poro-elastoplastic materials and the mobile Maykop shale is modelled as visco-plasic material.

The modelling results show that the atypical growth-strata geometries on the fold flanks can be explained by both the application of tectonic shortening and sediment loading of the visco-plastic layer. Comparing modelled growth-strata geometries with seismic data demonstrates that both the viscosity and density of the shale layer control the effect of differential loading and amount of fold amplification. Mechanical properties of 10^{18} Pa.s viscosity and 30% porosity for the visco-plastic shale layer provide the best fit between the model and the real data. The sensitivity of the model to shale and overburden thickness and applied tectonic shortening was tested. Results demonstrate that, whilst the fold location and initiation is controlled by a deep basement fault, fold geometries are controlled by the distribution of sediment between the crest and flanks of the structure. Less sediment over the crest compared to the limb causes more shale to move into the fold core with greater amplification of the fold.

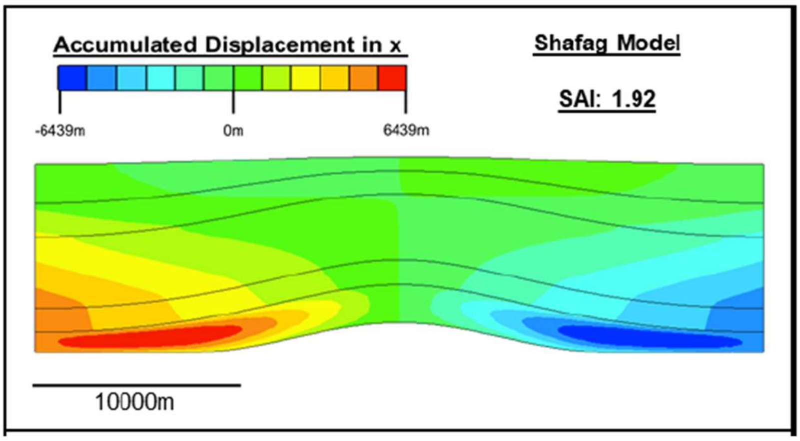

Figure: Cumulative *displacement in x at the end of the model run- the lowermost layer is the mobile shale; note how the shale has moved from the flanks towards crest of the fold*

Spatial and temporal variations in slip rate across extensional fault networks

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Slip-rate is a key input for seismic hazard assessment; however, slip-rate has been observed to vary in space and time along both active and inactive faults. Temporal variations in slip-rate have been used to imply the clustering and anti-clustering of earthquakes. However, most work to date has focused on slip rates measured at single locations and therefore lacks the combined spatial and temporal assessment of individual faults and fault networks. Here we present slip-rates derived from an inactive normal fault network within the Chandon3D seismic reflection survey, offshore NW Australia. We show spatial and temporal slip-rate variations over million-year time scales, along both single faults and across the fault network. The data show that the slip rate on individual faults can vary by over an order of magnitude. Slip-rate profiles along individual faults varied through time, with the location of maximum slip-rate moving by kilometres between time periods (Fig 1). We suggest that the likely cause of this variability is fault interaction during rifting, rather than changes in the rate of plate motion. Slip-rate variations have large implications for the seismic hazard assessment of active faults and thus our work raises the question whether single slip-rate measurements are sufficient to assess the seismic hazard posed by a fault.

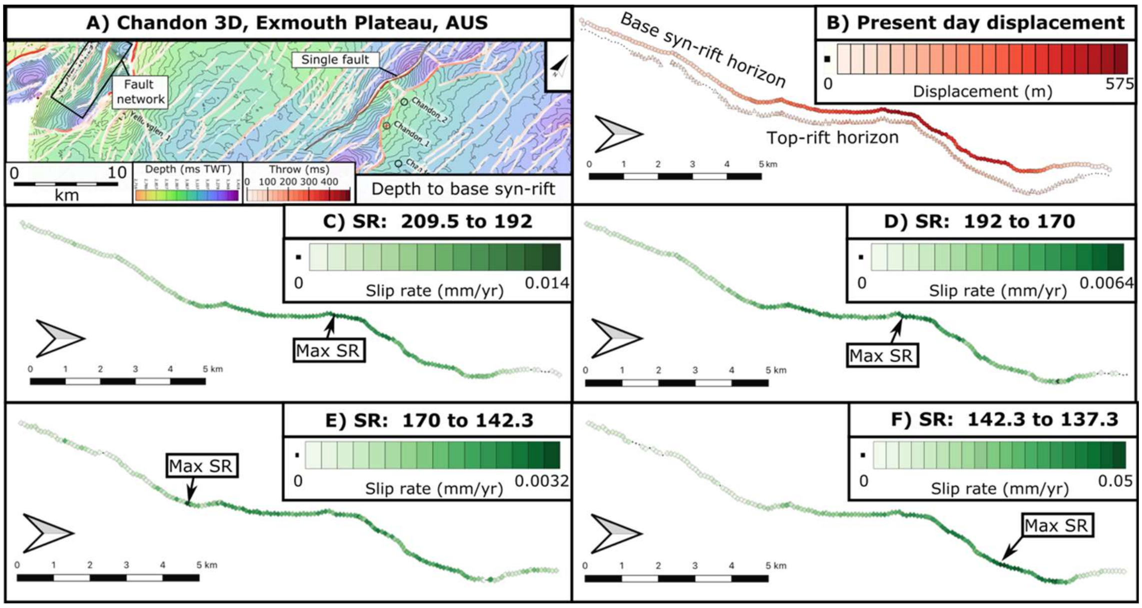

Figure 1: Slip-rate variations along a single fault. A) Depth to base syn-rift showing the distribution of throw across the study area. B) Throw across the base syn-rift and top-rift horizons. C-F) Slip-rate along the single fault with the location of maximum slip rate (SR) indicated.

Fissure fills and dykes: the geology of near-surface faulting in basement terrains

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[1,2]Ken McCaffrey

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The development of sub-vertical fissure systems has been largely neglected in basement terrains. Recent mapping on the Isle of Lewis, NW Scotland shows that these features are widespread and display remarkably diverse and complex geological characteristics. Where best developed, the fissures are kilometres long, 10s of metres wide and have an across-strike frequency of >10/km. The fissures typically preserve high porosity, multi-phase collapse breccias and sediment infills, with extensive carbonate-zeolite mineralization, and wall-parallel faults with dip-slip to oblique-slip slickenlines.

Sub-vertical NW-SE faulted fissure fills up to 30m wide are best exposed in W Lewis where they have strongly influenced the location and trend of Cenozoic dykes. Many dykes show evidence of interactions between magma and wet (and therefore contemporaneous) fissure fill sediments. Most fissures follow pre-existing NW-SE regional joint and fault systems, some of which are associated with base sulphide mineral veins. Pyrite from one of these precursor basement-hosted veins at Dhail Mohr yielded a Re-Os age of ca. 1456 Ma.

Similar basement (and cover) hosted fissure systems are recognized all along the Rona Ridge, an upfaulted basement high that lies along strike of the Hebridean chain. These fissures are known to profoundly influence fluid flow and storage in fractured basement reservoirs, most notably in the Clair and Lancaster fields. Very similar fissures are widely recognised associated with cratonic weathering profiles and hard rock aquifers worldwide. The exceptional exposures on Lewis therefore give a unique opportunity to better understand the geology and evolution of these hitherto little studied features.

An active fault database for the Luangwa Rift, Zambia: implications for continental rifting in thick lithosphere

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New geodetic evidence has revised the location of active plate boundaries at the southern end of the East African Rift System. However, knowledge of active faults along the newly discovered plate boundaries is lacking. This presents challenges for assessing seismic risk in these regions where the vulnerability to earthquake shaking is high, and the population is rapidly growing and urbanising, yet the earthquake hazard is poorly constrained.

We present a new active fault database for the Luangwa Rift in Zambia, the most active rift segment along the newly discovered plate boundary, which contains 18 active faults between 9 and ~200 km long. By analysing high-resolution topography, we show how active faults in the Luangwa Rift reactivate a Permian-Jurassic rift, with late-Quaternary fault scarps up to ~20 m high formed by multiple earthquakes. The orientation of the faults align with a late Proterozoic lithospheric-scale shear zone. Deformation within the rift is focussed on two >140 km long large offset border faults at the rift edges, which may be capable of earthquakes >M_w 7.8. The distribution of deformation suggests that the faults have formed in strong lithosphere with a strong upper and lower crust. This is confirmed by evidence from receiver functions and ambient noise tomography. We discuss the mechanisms facilitating rifting in strong, thick lithosphere at the southern end of the East African Rift System. Furthermore, we demonstrate how systematically building active fault databases provides a pathway for improved seismic hazard assessment, even in areas with few prior tectonic constraints.

Determining the origin and evolution of tectonic structures on Mars from surface data

[1*]Claire Orlov, [1]Emma Bramham, [1]Mark Thomas, [1]Sandra Piazolo, [2]Paul K. Byrne, [1]Estelle Mortimer

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With the aim of understanding the origin and evolution of tectonic structures at Mars's surface, we investigated an extensive plateau region called Tempe Terra using high resolution surface data. Tempe Terra has a large number of extensional structures that form part of the Tharsis Rise – Mars's largest volcano-tectonic province. From a starting point of satellite imagery and topographic data, we mapped over 23,000 normal faults, identified 16 unique fault sets, and their relative and absolute timing, to show Tempe Terra has experienced a multi-phase deformation history with three distinct stages of tectonic activity spanning hundreds of millions of years early in Martian history. We then further analysed our surface fault data to identify sources of faulting through time by comparing characteristics of the different fault populations to expected signatures of diverse kinematic models of fault formation. We used extension and cumulative frequency distributions of fault length to examine how strain was distributed and how the style of faulting varied through time. We also investigated the likelihood of later fault reactivation through slip and dilation tendency analysis. Our results show that each of the major stages of tectonic activity in Tempe Terra has a unique formation mechanism that has influenced its expression. A combination of tectonic and volcanic processes at both regional and local scales have driven deformation, producing the complex fault patterns we observe. This knowledge can help us better understand the evolution of the Tharsis Rise, which is essential to our understanding of Mars's geologic history more broadly.

Fractures, Fluids, and Melts

The Evolution of Paleo-Porosity in Basalts: Reversing Pore-Filling Mechanisms Using X-Ray Computed Tomography

[1,2,3*]Alice Macente, [2,3]Katherine J. Dobson, [4]John MacDonald, [5]Fabian B. Wadsworth, [6]Jeremie Vasseur

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Basaltic rocks are considered excellent candidates for CO2 storage by in situ mineral trapping, due to their large presence on Earth' surface and their higher reactivity with CO2 to form calcium-rich minerals. Often carrying a high-volume fraction of vesicles, basaltic rocks can be an important reservoir horizon in petroleum systems. When the vesicle network has been filled by earlier mineralization the basalts can act as impermeable seals and traps. Characterizing the spatial and temporal evolution of the porosity and permeability is critical to understand the CO2 storage potential of basalts. We exploited X-ray computed tomography (XCT) to investigate the precipitation history of an amygdaloidal basalt containing a pore-connecting micro-fracture network now partially filled by calcite as an analogue for CO2 mineral trapping in a vesicular basalt. The fracture network likely represents a preferential pathway for CO2-rich fluids during mineralisation. We quantified the evolution of basalt porosity and permeability during pore-filling calcite precipitation by applying novel numerical erosion techniques to "back-strip" the calcite from the amygdales and fracture networks. We found that permeability evolution is dependent on the precipitation mechanism and rates, as well as on the presence of micro-fracture networks, and that once the precipitation is sufficient to close off all pores, permeability reaches values that are controlled by the micro-fracture network. These results prompt further studies to determine CO2 mineral trapping mechanisms in amygdaloidal basalts as analogues for CO2 injections in basalt formations.

Interplay between fluid flow and rock deformation in an exhumed hydrothermal fault-vein network

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Faults can act as conduits for the migration of hydrothermal fluids in the crust, affecting its mechanical behaviour and possibly leading to earthquake swarm activity. To date, there are few constraints from the geological record on how fault-vein networks develop through time in high fluid-flux tectonic settings. Here, we describe small displacement (<1.5 m) epidote-rich fault-vein networks cutting granitoids in the exhumed Bolfin Fault Zone (Atacama Fault System, Chile). The epidote-rich sheared veins show lineated slickensides with scattered orientations and occur at the intersections with subsidiary structures in the fault damage zone. FEG-SEM cathodoluminescence (CL) reveals that magmatic quartz close to the sheared epidote-rich veins is affected by (i) thin (< 10 µm) interlaced deformation lamellae and (ii) a network of CL-dark quartz epitaxial veinlets sharply crosscutting the lamellae. EBSD maps of the deformed quartz indicate minor lattice distortion associated with the lamellae and an orientation nearly orthogonal to the c-axis. These deformation features disappear moving away into the host rock. The epidote sheared veins (i) include clasts of magmatic quartz with both the deformation lamellae and the healed veinlets and (ii) show cyclic events of extensional-to-hybrid veining and shearing. We propose that the microstructures preserved in the quartz next to the sheared veins record the high-strain rate loading associated with dynamic crack propagation and rapid micro-fracture sealing. On the other hand, the cyclic dilation and shearing within the epidote-rich veins is interpreted as the expression of a highly connected fault-vein network dominated by pore pressure oscillations leading to seismic swarm activity.

Fracturing in a mechanical multilayer under extension: natural examples and numerical modelling

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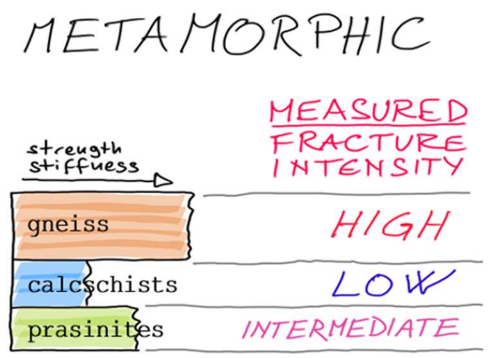
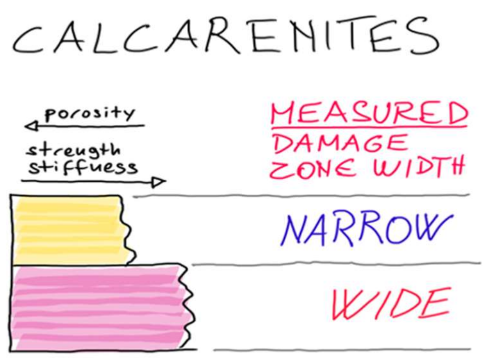
Improving our understanding of natural fracturing processes thanks to outcrop observations and mechanical modelling can help modelling fracture networks in reservoirs of geofluids. Here we investigate mechanically layered sequences of different rocks that show a more intense fracturing, both in terms of fracture density/intensity and number of fracture sets, in more competent layers. This qualifies as a very general behaviour since it has been observed and quantified in both porous calcarenites of the Island of Gozo (Malta), and in metamorphic rocks (gneiss, prasinites and calcschists) in the Alps (Aosta Valley, Italy, thanks to ReservAqua INTERREG Project). Simulations with analytical methods and a FEM code show that, during horizontal extension of a multilayer with variable elastic properties, deviatoric stresses build up much more quickly in stiffer rocks. This is because all the different layers are subject to the same horizontal strain, and stress is controlled by the elastic moduli, resulting in higher deviatoric stresses in more rigid layers. At some point, brittle failure (plastic yield in continuous FEM) takes place in the stiff layers, well in advance with respect to failure in the soft ones. At this point, the simulation reveals a situation where fracturing is confined in the stiff layers. As horizontal stretching continues, failure can occur also in the soft layers, but always in a more limited way. Understanding this mechanical behaviour, and how it applies in a very general way, might result in a revaluation of paradigms used to predict fracturing and hydraulic properties of mechanically layered reservoirs.



NW Alps (Monopoli et al. 2022, EGU)



Gozo (Malta) calcarenites (Martinelli et al. 2020, JSG)

Deciphering tectono-magmatic relationships across southeastern Iceland through palaeostress reconstruction from fault/fracture analysis

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This study presents a new interpretation for the palaeostress regime across southeast Iceland and discusses how the associated tectonic deformation patterns may control the geometry and distribution of magma emplacement across the region. We present quantitative fracture analysis arising from UAV-based photogrammetric structural mapping of the host rock surrounding the Reyðarártindur intrusion in southeastern Iceland and compare these data with historical regional mesoscopic fault slip analysis and associated stress patterns. The geometric pattern of the NE-SW and NNE-SSW principal fault populations surrounding the Reyðarártindur intrusion can be correlated with sinistral Reidel (R), and antithetic Riedel (R') conjugate shears, respectively, which form part of an WSW-ENE orientated, sinistral Riedel shear system. The inferred Riedel shear system is interpreted to have formed within a Neogene WSW-ENE trending transfer zone across southeastern Iceland that possibly linked at least two rift segments. Based on these observations, the roles Riedel shear systems and associated deformation patterns in transfer zones play in controlling the transport and storage of magma is discussed.

Reliability of automated fracture detection methods from decimeter resolution aerial imagery

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The reliable characterization of fracture network is vital for understanding fluid flow through rocks, particularly for those with low matrix permeabilities such as crystalline igneous rocks. This has a broad range of geoenergy applications, such as the transport of contaminants at geological disposal sites and the production of fluids and associated recovery of mineral rich brines in geothermal developments. The proliferation of decimeter-resolution imagery affords the opportunity to characterize structural lineaments in across large and previously difficult to access locations, and notably the digital data enable the use of reproducible automated interpretation methods. The adoption of automated interpretation methods amongst the geoscience community has increased as 1) the subjectivity of interpretations is reduced, 2) they can be more efficient, and 3) results can be reproduced. When adopting automated feature detection for faults and fractures it is essential that the methods produce reliable results. Many existing methods have been demonstrated – and possibly developed – using selected high-resolution images (often ~1cm/pixel) over laterally restricted exposures. However, many areas covered by existing aerial imagery have decimeter resolution.

This study investigates the effectiveness of automated lineament detection for faults and fractures from decimeter resolution imagery. Four different locations each with a different rock type and different image properties have been investigated. The study uses an existing contrast-based detection method and investigates the impact of contrast cut-offs and exposure continuity on the reliability of the extracted lineaments. Results show that: 1) lineaments tend to have fewer intersections as contrast cut-off is increased; 2) as the contrast cut-off is increased, so the number of lineaments <2m decreases; 3) outcrops with less continuous exposure generally results in less reliable interpretations; 4) the reliable detection of meter scale discontinuities requires a contrast difference between fracture and rock mass of at least 40%.

The findings here suggest that when utilising automated lineament analysis for fault and fracture interpretations, users should evaluate the how variations in image threshold parameters impact the resultant lineaments detected. The use of automated methods requires that users have a clearly defined criteria to QC the lineaments detected.

Geo-resources and Applied Structural Geology

GEOSOLUTIONS LEEDS-sponsored session

KEYNOTE PRESENTATION

Why reliable and reproducible structural interpretations are key for future energy projects

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The shift to expand the availability of low carbon electricity and heating and cooling will require continued subsurface characterisation to support the development of carbon capture storage, energy storage, geothermal energy, and radioactive waste disposal. In all cases there is the need to establish reliable interpretations of the subsurface to, as far as possible, eliminate any potential negative effects and risks, and to maximise project value.

Reliable (and reproducible) structural interpretations are required for the analysis of, for example, fault seal for storage integrity and the connectivity of fractures in low matrix permeability rocks for geothermal energy and radioactive waste disposal. To quantify the reliability and uncertainty in structural interpretations, specifically where they make use of geophysical data, requires the input data, methodologies used, and interpretations all to be available and accessible. In recent research, based on a random sample of published geophysical research between 2019 and 2021, it was found that less than 30% of articles provided enough information to reproduce the results. Principally this was related to the accessibility of data and interpretations.

Despite the critical role of structural interpretations from geophysical data will likely have in energy developments, at least for published articles, the data and interpretations are frequently not accessible. Whether this extends to ‘grey literature’ is yet to be established. Regardless, in the future, clearly directed reporting of data, interpretations and methods should be central in ensuring the safe and reliable operation, and post closure monitoring, of subsurface energy developments.

The impact of fault interpretation strategies on fault patterns

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The ability to map faults is a fundamental requirement of almost all interpretations of subsurface geological structure. Fault interpretation techniques, in 3D seismic volumes, have been widely analysed from the perspective and interest of industries that extract natural resources (e.g., oil and gas, mining). In addition, there has been significant effort made to study large faults because they control reservoir architecture. These methodologies usually include simplifications and carry high uncertainty. However, how do these simplifications and the associated uncertainty compromise fault statistics? Understanding the impact of fault mapping strategies on fault statistics is critical for assessing interpretational failures and uncertainty risk. As we enter the Energy Transition, it is essential to think about how fault mapping challenges will influence the future integrity of subsurface geo-storage sites and energy extraction. Here, we examine the sensitivity of output fault geometries derived from five distinct interpretational workflows applied to a high-quality 3D seismic volume. This work aims to determine how distinct fault mapping strategies influence fault geometry and connectivity through the analysis of their statistics. Two controlling factors impact fault patterns and their derived statistics (mean, standard deviation, median) most – fault picking and under-sampling. Our results show that different workflows generate different interpretations of fault geometry and yield distinct statistics. We emphasise the importance of fault mapping techniques in fault analysis and suggest that statistical fault analysis should be accompanied by careful descriptions of mapping workflows. Multiple workflows should be used at least to initiate appreciation of the uncertainties in these interpretations and the impact on fault statistics.

Variation of structural style across the Yorkshire Wolds Chalk aquifer: recent findings from field mapping campaigns and seismic interpretation

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The Chalk Group aquifer provides the main source of water supply in East Yorkshire. Its configuration, including the effects of faulting, influence groundwater flow across the region. Some areas of the Yorkshire Wolds Chalk aquifer have not been systematically mapped since the early 20th century, and do not reflect present-day stratigraphic divisions or current tectonic understanding. A multi-faceted approach to geological mapping is being undertaken in the region by the British Geological Survey, in collaboration with the Environment Agency and Yorkshire Water, integrating remote sensing, targeted field mapping, palaeontological analysis and 2D onshore seismic interpretation.

The Flamborough Head Fault Zone (FHFZ) has a complex history of reactivation in extension and compression during the Mesozoic and Cenozoic. The fault zone forms an E-W trending graben structure which is bound by listric faults. In the northeastern Wolds, the N-S trending faults of the Hunmanby Trough cross-cut the E-W faults of the FHFZ. In recent field campaigns, evidence has been found for greater structural complexity, including fault orientations oblique to the main trends. South from the FHFZ the deformation decreases and the structural style changes from tilted fault blocks within grabens to gentle folding (bedding dip not exceeding 2° in most cases). Understanding the style and trend of the folding is key to accurately mapping the stratigraphic contacts of units with differing hydraulic properties in the poorly exposed inland mapping area.

We present structural sections based in 2D seismic interpretation and new field observations from the northwest Yorkshire Wolds which contribute to the understanding of the structure of the Chalk aquifer, with the aim of improving the management of water resources.

Section restoration and the structural setting of the candidate rad-waste repository in the Jura fold-thrust belt, Switzerland

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The Jura hills, on the outer margin of the NW Alps, is classically interpreted as a "thin-skinned" fold-thrust belt, detached along Triassic evaporites. It includes the Opalinus Clay (Toarcian-Aalenian), the designated host formation for a radioactive waste repository in Switzerland. Here we develop a case study to illustrate how methods and approaches in cross-section balancing and restoration, based on seismic imagery, can be applied to assess risks and uncertainties for the integrity of the Opalinus Clay in areas targeted for future repositories (Nördlich Lägern). 3D seismic mapping defines a largely unfaulted domain within which there is no indication of deformation in the Opalinus. It is however seismically transparent. This "low-strain" domain has been translated tectonically and is bounded to the north and south by domains of strongly-faulted Mesozoic strata. These overlie a seismically-imaged Permo-Carboniferous basin and its bounding faults. Multiple interpretations of structural style, the continuity and relative timing of structures have been developed, identifying key uncertainties for determining risks of compromised structural integrity in the prospective repository site: did the Opalinus Clay act as a regionally extensive thrust detachment interval; were the thin-skinned thrust structures influenced by deep basement structures (that might reactivate in the future)?

Has the Opalinus acted as an intraformational detachment that connected kinematically the northern and southern deformation domains? Section balancing and restoration are used to assess whether strain in the two deformation domains can be matched on both sides of the Opalinus Clay. If not, then there is an increased risk of the Opalinus having acted as a detachment – passing through the "low strain" domain (candidate repository site). Combinations of line-length and formation area balancing have been applied to both bounding deformation domains, using different workflows and interpretations of fault trajectories. In all these interpretations, a balance in tectonic contraction can be achieved – without involving distributed strain or requiring detachment within the Opalinus. On this basis, the structural integrity of the prospective repository site is not compromised – an inference consistent borehole evidence. No significant layer-parallel fault zones have been identified in the four penetrations across the Nördlich Lägern site. However, detachment within evaporitic levels near the base of the Triassic, as encountered in boreholes, may have been modulated by short-lived reactivation of basements faults especially localising the southern deformation domain. This raises issues as to the timing of formation of the northern deformation domain with respect to the southern one – and therefore for thrust sequencing in the outer part of the Alps. As for risks to a radioactive waste repository at Nördlich Lägern, the locus of potential basement reactivation is located outwith the "low-strain domain" – the preferred repository site.

Natural and engineered fractures in the energy transition: learnings from core, models, and outcrops

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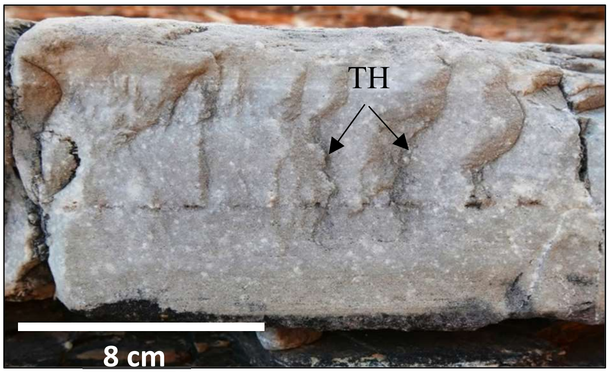
Characterization and prediction of natural and engineered fractures have been essential endeavours for mining, geotechnical engineering, and hydrocarbon production. Understanding natural fractures has improved through recognition of the role of chemistry in fracture pattern development. In applications where natural fractures are insufficient as fluid flow pathways, hydraulic fracturing has been used to enhance the fracture network. The desire to optimize stimulation and mitigate problems has driven recent experiments in shale hydrocarbon reservoirs where core was acquired after stimulation, allowing direct observation of hydraulic fractures. We present a summary of results from these experiments and discuss hydraulic fracture network development, including mechanisms for generating complexity. Core, analogue models, and outcrops show that complexity can arise with or without pre-existing opening-mode fractures or faults (Figure 1). We assess the role of natural and engineered fractures in transitional energy projects where flow pathways are critical, with examples from a low enthalpy geothermal project, and CO_2 storage in unconventional reservoirs and ultramafic rocks.

(a)

(b)



(c)

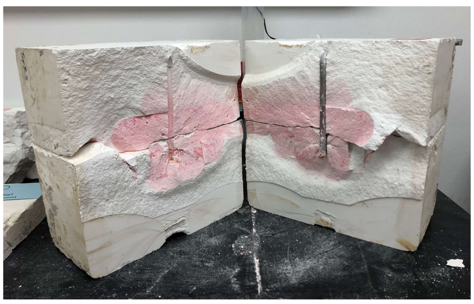


Figure 1. (a) Core (10 cm diameter) with bifurcating hydraulic fractures, (b) outcrop fracture face with segmentation twist hackles (TH) in upper half, (c) analogue model of fracture growth pulled apart to show red-stained fracture plane. Block is 31.5 cm in height.

Strain, Rheology, and Microstructures

KEYNOTE PRESENTATION

Stress fields of dislocations in quartz from the Karakoram Fault Zone and their role in transient creep of the continental crust

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Geological processes, such as major earthquakes, that impose changes in stress on viscoelastic rocks in the lower crust and upper mantle induce a period of transient creep involving evolution in microstructure, micromechanical state, and effective viscosity. However, geodetic data on transient creep are typically analysed using phenomenological models that lack a basis in underlying physical processes due to a lack of experimental and geological constraints on the dominant microscale mechanisms. Nonetheless, recent experimental results indicate that transient creep results from elastic interactions among dislocations via their long-range internal stresses. These interactions generate an evolving back stress that counteracts the applied stress causing an evolution in effective viscosity. Here, I test for the presence of long-range internal stresses generated by dislocations in quartz from the mid-crustal shear zone of the Karakoram Fault Zone to assess the relevance of this potential mechanism of transient creep to natural deformation. High-angular resolution electron backscatter diffraction reveals stresses that vary in magnitude by several hundred megapascals over length scales of several micrometres within grain interiors. The stress heterogeneity is collocated with regions of elevated dislocation density within each sample and also increases in magnitude between samples along a transect from the margin to the interior of the shear zone. Moreover, the probability distributions of the stresses have tails that decay as the inverse cube of the stress, which is a diagnostic characteristic of the stress fields of dislocations. These results confirm the presence of long-range internal stresses generated by dislocations in a mid-crustal shear zone and thereby support the application of models of transient creep based on the evolution of a dislocation-induced back stress that counteracts the applied stress.

Strain Localisation in Oceanic Detachment Faults: Are Serpentine and Talc Weak Minerals?

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Oceanic core complexes are domal massifs formed at spreading ridges capped by detachment faults. These faults evolve by flexure from steep to shallow attitudes, and have typical displacements in the Atlantic of ~10 km. They form at slow spreading rates, often at the inside corners of ridge-transform intersections, where magma generation is insufficient to keep pace with the separation rate by magmatic intrusion. OCCS expose mantle rocks and gabbros on the seafloor, and host important hydrothermal fields such as Lost City.

Detachment fault rocks have been recovered by drilling in two locations in the Atlantic, a massif at 15° 45’ N, and the Atlantis Massif at 30° N. High temperature mylonitic fault rocks are rare, and are overprinted by brittle fault rocks (even at temperatures > 700 °C), and greenschist grade talc-tremolite-chlorite schists. Strain is sometimes localised into schistose talc, but fine-grained talc rocks overprinting serpentinite are usually undeformed. In IODP 357 cores, typical shear zone fabrics show that strain was localised into metasomatic talc-tremolite-chlorite schists, but within those schists, lenses of chlorite with random talc laths are undeformed compared to adjacent fine grained tremolite which may have deformed as cataclasite before limited grain growth. Breccias affect all previous lithologies and fault rocks, including serpentinites, but no schistose fabrics in serpentinite have so far been recorded.

Data so far suggest that serpentinite is not the predominant fault rock in detachment fault zones. More complete sections of the Atlantis Massif detachment fault zone will be collected on IODP Expedition 399, April to June 2023.

Stresses of seismic rupture propagation preserved in the lattice of faulted garnets

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The stress history of seismogenic faults varies over orders of magnitude in space and time. Differential stress builds up to hundreds of MPa to GPa during the loading stage and it is released abruptly in a sequence of events (rupture propagation, frictional fault slip, thermo-mechanical interactions) determining extreme stress perturbations. This complexity hampers the measurement of these stresses from microstructural proxies in the geological record.

Here, for the first time, we measure with high-angular resolution electron backscattered diffraction the residual stress retained in the lattice of seismically shocked garnets crosscut by a pseudotachylyte fault vein (i.e., along the fault slip surface). The mm-thick, pristine pseudotachylyte vein was produced during a single seismic event at mid-crustal conditions (approximately 500 MPa, 500 °C) within felsic gneisses in the hanging wall of the Woodroffe Thrust (Musgrave Ranges, central Australia). Garnets are intensely fractured and show extreme comminution close to the pseudotachylyte. Residual stresses increase from a few hundreds of MPa at 1 mm of distance from the pseudotachylyte up to 5-6 GPa in contact with it, together with increasing geometrically necessary dislocations density. High stress domains, a few micrometres in size, are bounded by straight bands of stress sign inversion, that become irregular and more closely spaced near the pseudotachylyte. Garnets microstructures, stress gradients, and stress magnitudes all suggest that the extreme residual stresses measured in proximity to the pseudotachylyte belong to the stage of earthquake rupture propagation, in agreement with the stress fields predicted at the tip of a propagating fracture.

Using kyanite to constrain changes in deformation regime and partial melting during metamorphism

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Kyanite is a common major mineral within metapelites experiencing medium to high pressure metamorphism under an array of temperature conditions. Kyanite is mainly used to constrain *P*–*T* conditions as a part of a metamorphic assemblage, as a constituent or porphyroblastic marker in deformational fabrics and as evidence of certain deformational conditions from internal features such as kink bands. A recent study identified that kyanite can preserve an array of internal zoning, even when deformed. However, to utilize zonation patterns for petrological and tectonic studies, details how such how zonation pattern link to conditions and processes of formation and/or deformation must be first established.

In our study, we utilize a sample from South Harris, NW Scotland. South Harris, Scottish Outer Hebrides, represents a suture zone between two basement terranes of Archean age, the Uist Block to the south and Tarbet Terrane to the north. The suture zone contains slivers of metapelitic rocks which experienced a complex *P*–*T* path. Kyanite within an example of these complex metapelites displays multiple populations based on petrology. These generations display different deformational markers as well as internal zoning and trace element patterns. Using a combination of petrology, EBSD, CL imaging and EPMA we correlate these textural populations of variably deformed kyanite to the partial melting history and changing deformational regime. Our study shows that zonation patterns in kyanite can indeed be used to derive conditions of formation and/or deformation through in depth multi-analyses.

The seismic cycle in bituminous dolostones (Central Apennines, Italy)

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Central Apennines in Italy is one of the most seismically active areas in the Mediterranean (e.g., L'Aquila 2009, Mw 6.3 earthquake), with mainshocks and aftershocks propagating along extensional faults cutting km-thick sequences of carbonates. The same fault can record several short-lasting seismic events, episodic to continuous creep and fault locking during the inter-seismic phase. Given the broad range of loading conditions, several mechanical and chemical processes operate in fault zones: fracturing, crystal-plastic deformation, dissolution and precipitation, etc... We document the interplay between these deformation mechanisms in normal faults cutting through bituminous dolostones in the Central Apennines. We sampled faults of increasing displacement (from < 1 mm to few meters) and with ultra-polished slip surfaces ("mirror-like surface").

Microstructural analysis of the slip zones show evidence of cataclasis, pressure solution and smearing of bitumen. Furthermore, the fault surfaces with higher displacement also record multiple slip events with ingression of carbonate-rich fluids and fragments of older slip zones sealed by calcite precipitation. Sometimes, these fragments derive from bitumen-rich slip zones with evidence of viscous flow. We propose that these microstructures preserve the evidence of multiple cycles of 1) high strain rate coseismic embrittlement (i.e., fragments of previous slip zones associated to fluid ingression), long-term aseismic or post-seismic creep (i.e., bitumen viscous flow and pressure solution) and fault locking/sealing (i.e., calcite precipitation). Since mirror-like surfaces can form both during seismic slip[1–4] and aseismic creep[5,6], this study present a natural case of different processes acting in the same slip zones throughout the seismic cycle.

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Rifting, Basins, and Sedimentation

Topological characterisation of rift margin fault network, northern North Sea rift system

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The topological analysis of rift fault networks can provide important insights into the connectivity of normal faults and the understanding of the structural complexity of rift systems. Using broadband 3D seismic reflection data from the northern North Sea, we analyse the spatial variation of the geometry and topology of the Late Jurassic normal fault network along the rift margin. Our results show that fault orientation varies spatially along the rift margin, i.e., normal faults within fault blocks that are adjacent to the North Viking Graben exhibits dominant N-S and NE-SW strikes that are sub-parallel to the graben axis and associated step-over, whereas in fault blocks farther from the graben, there is a dominant NW-SE strike. Furthermore, we identify two broad topological domains within the fault network: 1) dominated by isolated (I-) nodes, partially connected (I-C) branches, low fault density and connectivity, and 2) dominated by abutting (Y-) nodes, fully connected (C-C) branches, moderate to high fault density and connectivity. These topological domains correlate with previous sub-division of the rift margin in the northern North Sea into platform and sub-platform structural domains, respectively. There is also a positive correlation between the spatial variability of the fault orientations and density, with the fault network connectivity, highlighting the relationship between normal fault geometry and topology. We conclude that the across and along-strike variation in strain, presence of pre-existing structures, and accommodation zone-related deformation are key factors influencing the spatial variation of fault network properties at the rift scale. This study also provides a new way of characterising large-scale structural domains in rift systems.

Comparing intrarift and border fault structure in the Malawi Rift: Implications for normal fault growth

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Early stages of normal fault growth are seldom described using field observations of active normal faults. Here we first estimate the displacements of active border and intrarift faults in the Zomba Graben in the low extension (<10%) Malawi Rift, and then quantify micro-to macroscale fault damage and mineralisation associated with their surface exposures. The 22 km long Mlunguzi and 39 km long Chingale Step intrarift faults, have fault zones 4–52 m wide. In contrast, we estimate the fault zone of the 51 km long Zomba border fault is 32–118 m wide. Calcite and clay alteration is limited to the fault damage zones and fault cores, and the extent and intensity of fault damage and mineral alteration is greater on the Zomba border fault compared to the intrarift faults. Relative to global compilations, normal faults in the Zomba Graben have lengthened quickly while developing narrow fault zones, given their displacement. The minor damage on these long, low-displacement normal faults may reflect the influence of lithology, negligible fault healing, and/or activation of pre-existing weaknesses.

How and when do intraplate basins record deformations? A multiscale approach to Cenozoic deformations of the Paris Basin

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Intraplate sedimentary basins are essentially subject to tectonic stresses that propagate from plate boundaries. Yet, the detailed characteristics of this far field propagation are often poorly constrained, especially in age. This is the case for the Meso-Cenozoic Paris Basin, liable to have recorded several events due to its location in the western Eurasian plate, i.e. Pyrenean convergence, Alpine collision, and Oligocene extension. This study is involved in establishing the Cenozoic tectonic agenda using a multiscale approach. At regional scale, we interpreted the Meso-Cenozoic limit - using the top Cretaceous Chalk horizon as reference - on 5000 kilometers of reprocessed vintage industrial seismic lines calibrated with 100’s of wells with velocity surveys. Field investigations allow for the production of synthetic structural maps. We provide an absolute age for deformations with in-situ U-Pb dating of syn kinematic calcite, improving upon existing tectonic calendars based on relative chronology. Finally, the scarcity of outcrop data requires the determination of internal microscopic deformations using Anisotropy of Magnetic Susceptibility (AMS) and of P-Wave Velocity (APV).

The Meso-Cenozoic isohypse map reveals post Cretaceous folding at various wavelengths. Regional NW-SE and NE-SW asymmetrical folds exist along both borders of the basin. Field data reveal almost exclusively strike-slip deformations throughout the Paris Basin with a dominant ~N-S horizontal σ_1 changing locally from E-W to NW-SE. Associated U-Pb dating of syn kinematic calcites from Jurassic strata in the southeast of the basin indicates distributed Eocene deformation and an absence of Oligocene or Miocene ages, questioning the current established tectonic calendar.

A Pre-rift Low-angle Shear Zone: Its Origin and Influence on Rift Structure, Central Gulf of Thailand

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In Thailand, the location and geometries of many Cenozoic rift basins are inherited from the structural fabrics of a major Triassic Paleo-Tethys suture. However, the 3D reconstruction of such fabrics for a deep understanding of rift inheritance is rarely possible. Remarkably, 3D seismic reflection data from the western flank of the Pattani Basin in central Gulf of Thailand provides good-resolution pre-rift reflections. Only a small portion of pre-rift is penetrated by wells. Therefore, geological information from outcrops following the onshore suture trend was applied to offshore seismic interpretation. Three pre-rift units are identified: successively upward, (B1) high-grade metamorphic and granitic rocks; (B2) 1-km interval of mylonitic schist and gneiss; (B3) highly deformed Palaeozoic-Triassic marine sedimentary rocks and weakly deformed Cretaceous continental red beds. B3 is detached along its contact with B2, which comprises elliptical basins and domes about 20-30 km across displaying 2-3 km structural relief. Kinematic indicators in B2 mylonites indicate a uniform top-to-the-east shear. Mylonitisation probably took place during post-collision collapse and exhumation of the Triassic suture. The mylonites were subsequently subjected to large-wavelength folding prior to rifting. Seismic interpretation shows that syn-rift faults follow the flanks/limbs of the domes, such that the basin depocentres and regional highs coincide with B2 structural trend. Faulting was probably facilitated by both the mechanical properties and orientation of the shear zone. This study provides insights into the general theme of structural reactivation, how suture zones become reworked and exhumed, tectonics of Thailand and adjacent regions, together with implications for petroleum exploration in pre-rift basement.

How lithospheric thickness and strength variations facilitate the rifting of ancient cratonic lithosphere

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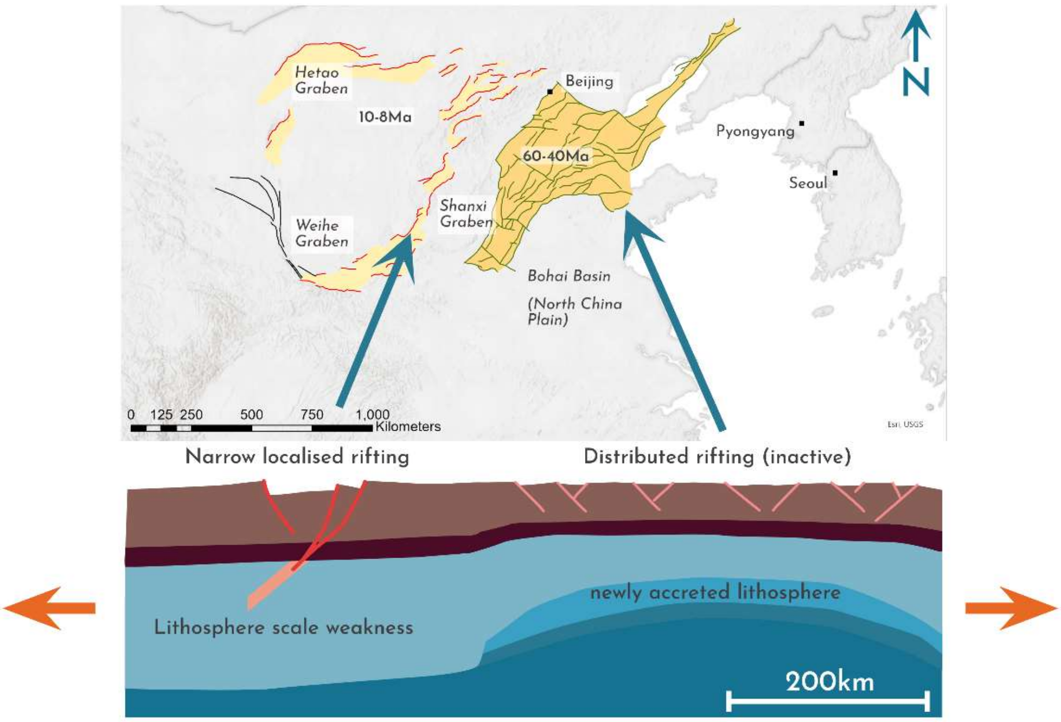
Geodynamic models can aid understanding the evolution of rifting in North China and other rift systems. The North China Craton (NCC) formed by the collision of two Archean blocks in the Paleoproterozoic forming the broad collision zone known as Trans-North China Orogen. The NCC shows two different modes of extension that are separated by space and time. In the Paleogene in the Eastern NCC wide, distributed rifts formed, in the Neogene rifting migrated to the Western NCC forming narrow rifts near Proterozoic orogens. However, the mechanism that led to development of these fundamentally different rifts and the migration of rifting remains debated. Here we use the geodynamical tool ASPECT to perform 2D thermo-mechanical modelling to explain the role of variable lithospheric strength and inherited lithospheric weaknesses in the development of rift systems. We found that a wide distributed rift develops over non-cratonic lithosphere, while the adjacent cratonic lithosphere will accommodate little strain. To explain rift migration in North China we require 1.) a period of tectonic quiescence that strengthens lithosphere following distributed initial rifting 2.) a specific range of relative lithospheric thickness variations and 3) presence of a lithosphere scale weak zone, i.e., an inherited feature. Our results show how lithospheric thickness and strength variations as well as discrete zones of lithospheric weaknesses can influence the style of rifting and facilitate the breakup of an ancient craton. These results are applicable to other multiphase rift systems around the world such as the North Atlantic.



Using U-Pb calcite geochronology to better constrain basin-bounding fault reactivation, Inner Moray Firth Basin, North Sea

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Like many rift basins worldwide, the Inner Moray Firth Basin (IMFB) is bounded by major reactivated fault zones including the Helmsdale and Great Glen faults (HF, GGF). These faults lack absolute age constraints for the timing of reactivation. The Jurassic successions exposed onshore close to these faults at Helmsdale and Shandwick localities preserve folding, calcite veining and minor faulting consistent with sinistral (HF) and dextral (GGF) transtensional movements, respectively. This deformation has previously been attributed to the Cenozoic post-rift fault reactivation during basin exhumation and erosion.

Fieldwork and U-Pb calcite geochronology provides new evidence for two phases of faulting during the Late Jurassic (c. 159 Ma, Oxfordian – HF only) and Early Cretaceous (c. 128-115 Ma, Barremian-Aptian – seen along both the HF and a splay of the GGF). These ages suggest that both basin-bounding faults were substantially reactivated during the protracted main phase of NW-SE-directed Mesozoic rifting that formed the IMFB. These and other recent findings in this supposedly well-understood basin highlight the importance of oblique slip reactivation processes in shaping the evolution of continental rift basins given that this deformation style may not be immediately obvious in interpretations of offshore seismic reflection data.

Convergent Margins, Intra-continental Plate Deformation, and Magmatism

Tectonic shortening structures in western Arabia Terra, Mars

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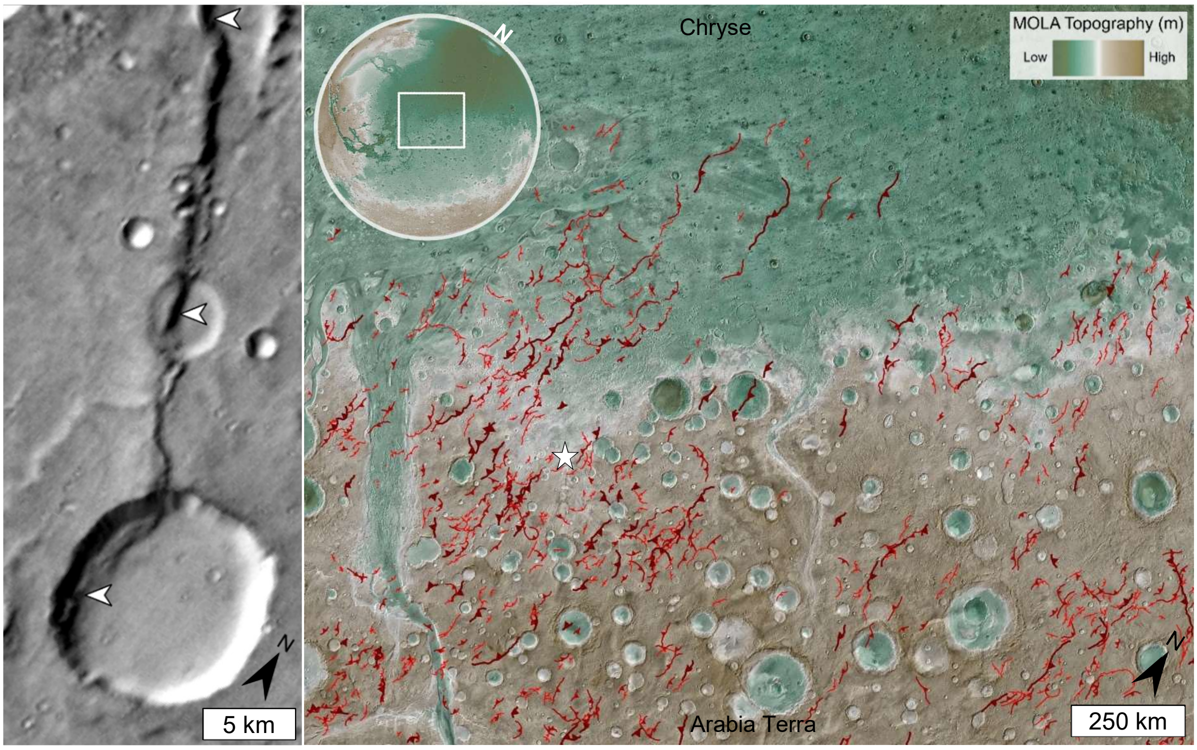
Mars has widespread tectonic features, globally mapped at a 1:20,000,000 scale [Tanaka et al. 2014, P&SS]. However, a more detailed survey is needed of the region surrounding the landing site of the ExoMars Rover, to provide insights into the region's tectonic evolution. We aim to investigate the properties of tectonic features and deformed terrain, the timing of tectonic activity, and the source(s) of stress. We conduct a detailed structural survey at 1:50,000 scale of a 3 million km^2 area, located in transitional terrain between Arabia Terra (ancient southern highlands) and Chryse Planitia (younger northern lowlands). We map 845 tectonic shortening structures, with a mean length of 33.2 km and a mean scarp height of 60 m, and analyse their orientation, distribution, and morphology. Additionally, to calculate displacement, we use the geometry of shortening structures cross cutting impact craters to measure the dips of 15 faults, as studies of Martian thrust fault dips are very limited.



Left) Example of a shortening structure (linear, NW-SE oriented, SW dip) deforming two impact craters. Shortening structures are interpreted as surface expressions of thrust faulting with a varying degree of folding. *Right)* Map of shortening structures in western Arabia Terra and Chryse Planitia. Star shows ExoMars Rover landing site.

3D structural modelling in the North-Western Alps (Aosta Valley, Italy): a powerful tool for exploring the tectonic evolution of the Alps

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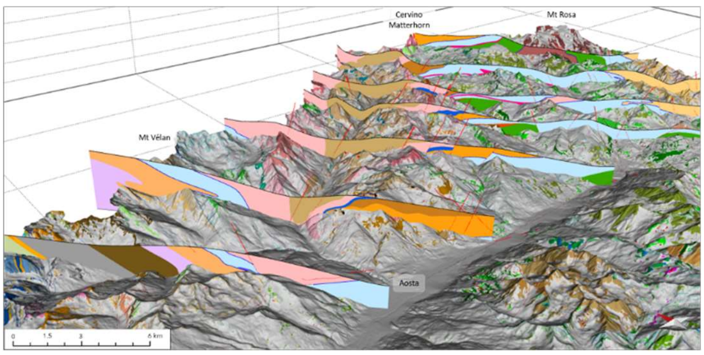
Three-dimensional visualisation and conceptualisation are always, knowingly or unknowingly, part of the process of studying a geological phenomenon. As a standard it is accepted that, when 3D structures are too complex to deal with, a two-dimensional study is the preferred way of simplifying a problem into smaller ones (*divide et impera*). Since Argand, in the case of tectonic interpretation studies, vertical cross-sections are appreciated since, if serialised, they can stand in for a 3D conceptual model. However, this method has limitations when interpreting non-cylindrical structures, as visualisation is confined to 2D formats.

Here we present the new 3D structural model of a portion of the North-Western Italian Alps, built in the context of the ReservAqua INTERREG project. Input data come from about 1300 km^2 of 1:10,000 maps with rich structural data and thousands of samples and thin sections. Thanks to the very rugged topography, with 4000 meters of elevation difference between the highest peaks (e.g., Cervino-Matterhorn) and the lowest valleys, this is a truly 3D dataset. After an orientation statistics study, the geological interpretation is performed on densely serialised cross-sections, eventually used to guide 3D interpolation with implicit algorithms.

In this contribution we focus on the structural principles that allow us building the array of cross-sections and the implications that these decisions have on the final 3D model. We also account for the beneficial effects that three-dimensional modelling has on the process of tectonic interpretation, and we discuss its applications in mountain ranges (hydrogeology, thermal springs, etc.).



Post-nappe brittle deformation in the NW Alps: age constraints from $^{40}Ar/^{39}Ar$ dating of pseudotachylytes

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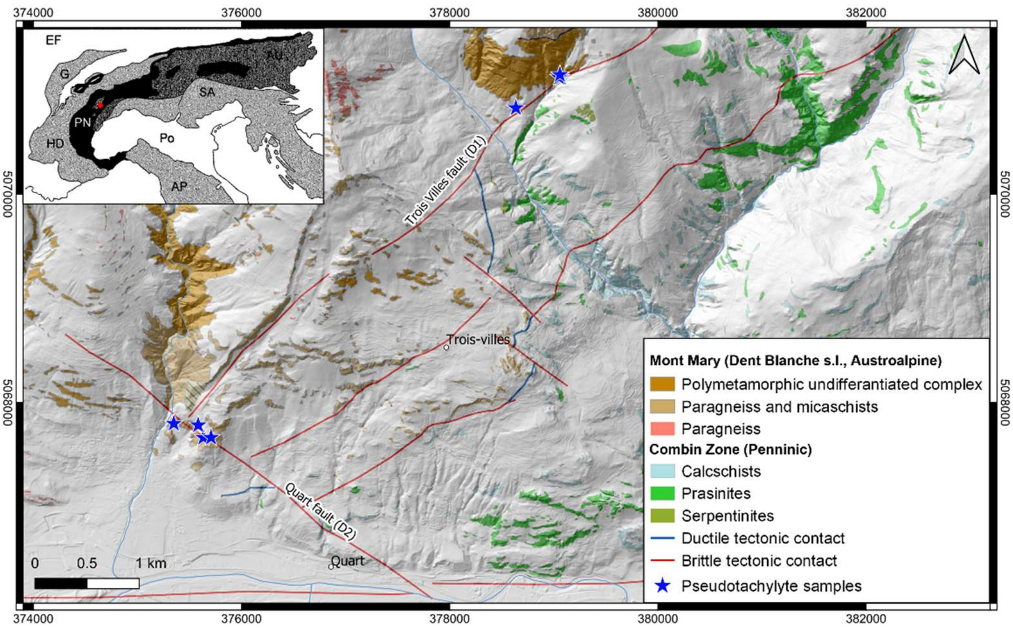
Although the geology of the north-western Alps has been studied for over two centuries, post-orogenic extensional brittle tectonics has been considered only in the last few decades. Three different deformation phases are identified: D1 is characterized by NW-SW extension, D2 by NE-SW extension and D3 by N-S extension. The relative chronology of these deformation phases is based on consistent cross-cutting relationships. D1 ages of 29–32 Ma have been inferred by dating syn-kinematic magmatic dikes and hydrothermal veins. However, direct radiometric dating of D1 fault rocks has never been performed, and no absolute ages are available for D2 and D3.

Here we present the results of step-heating $^{40}Ar/^{39}Ar$ analyses performed on samples of pseudotachylytes of the Trois Villes Fault (D1) and the Quart Fault (D2).
Microstructural analysis and microCT quantify the clast-to-pseudotachylyte matrix ratios for each sample, while the Ca/Cl/K signature provided by Ar systematics confirm the ubiquitous contributions from both the melt-derived matrix and inherited clasts. The D1 samples from Trois Villes shows Oligocene matrix ages (29 – 33 Ma) consistent with published results on dykes and veins, and inherited ages of around 55 Ma associated to clasts.

Our results re-iterate that pseudotachylyte $^{40}Ar/^{39}Ar$ results can only be interpreted reliably by combining a detailed microstructural study with the data on all five Ar isotopes.



Demonstrating Scandian age seismogenic deformation within the Moine Thrust Zone using in-situ Rb-Sr LA-ICP-MS

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The Moine Thrust Zone, the western boundary of Caledonian deformation in the British Isles, separates exhumed mylonitic Moine and Lewisianoid rocks in the eastern hanging-wall from mostly undeformed Caledonian foreland to the west. Evidence of seismicity during Scandian deformation is reported from the Outer Hebrides Fault zone (OHFZ) in the form of pseudotachylytes (PST) (430Ma Kelley et.al., 1994). Direct evidence of seismicity in the MTZ has been conspicuous by its absence.

We present documentation of PST generation in the lowermost composite Moine Thrust mylonite sheet ENE of Hope. The PST (Fig 1) cross-cuts mylonitic gneiss and is associated with cataclastic deformation and hanging-wall rotation. Importantly, PSTs are relatively common within the Lewisianoid foreland (OHFZ, Loch Assynt, Canisp and Gairloch), with ages from 1900, 1300-1200Ma (Sherlock et al, 2009), 1550Ma (Hardman et al., 2022) and 1019-910 Ma (Campbell et al., 2019). In isolation, the presence of PST in the Lewisianoid at Hope is not direct evidence of Scandian seismicity as it could be a relic of a much older event.

Age verification of the Hope pseudotachylyte used in-situ Rb-Sr LA-ICP-MS/MS analysis at the University of Hull LA-ICP-MS facility yielding a Rb-Sr isochronal age of 427 +/- 11.5Ma. This date constrains a change from ductile to brittle deformation and must be accommodated in future models of Scandian orogenesis in Scotland, and confirms the Moine Thrust was seismogenic during the Scandian orogeny.

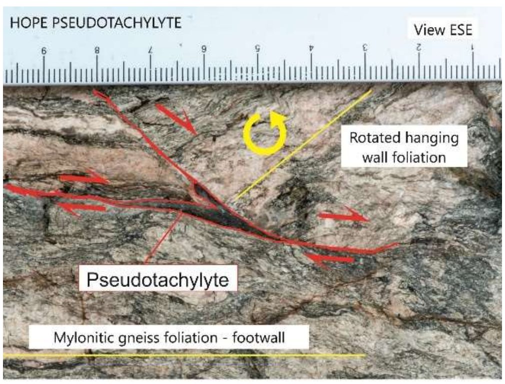

Fig. 1 Scandian age Pseudotachylyte (red) bearing fault within the Moine Thrust Zone at Hope cross-cutting mylonitic fabric (yellow) in lewsisanoid fault rocks

Kelley et.al. 1994 doi.org/10.1130/0091-7613(1994)022<0443:LPAAIO>2.3.CO;2;
Sherlock et.al. 2009 doi:10.1144/0016-76492008-125;
Campbell et.al. 2019 doi.org/10.1144/sjg2019-003;
Hardman et. al. doi.org/10.1144/jgs2022-037

Plate Tectonic Implications for a Quadrupolar Proterozoic Geodynamo

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Ultra-weak intensity of the Proterozoic paleomagnetic field suggests late Neoproterozoic to early Paleozoic inner core nucleation (Lloyd et al., 2022). It may indicate a weak multi-polar, rather than strong dipolar geodynamo. Re-interpretation of paleomagnetic data in the context of a multipolar magnetic field would require revision of Proterozoic paleogeographic maps and associated plate tectonic models. Here I plot Proterozoic supercontinent Nuna into a quadrupolar framework. Quadrupolar Nuna simplifies Proterozoic plate tectonic models and is geologically more robust than geocentric axial dipole (GAD) alternatives. The model presents precise geologic piercing points connecting Siberia, Laurentia, Baltica, Australia, and North China in a seamless tectonic mosaic. Facing conjugate margins exhibit closely correlative rift-to-drift stratigraphic sequences. Quadrupolar Nuna grew from systematic accretion of curvilinear crustal terranes. At ~2 Ga, a narrow granulite-facies belt sutured Archean cratonic assemblages into a continental nucleus having a deep, diamondiferous keel. A wide orogenic belt embedded with Archean blocks joined the nucleus at 1.9-1.8 Ga. Continental-margin magmatic and orogenic belts built the supercontinent outward in a stepwise fashion from 1.8 to 1.4 Ga, culminating with the Grenville orogeny and assembly of supercontinent Rodinia at 1.3-1.0 Ga. The Nuna component of Rodinia broke apart from ~950 Ma to ~550 Ma, with smooth dispersion of its member cratons. The model implies that the quadrupole transitioned to GAD in early Paleozoic times, with a ten-fold increase in paleo-intensity.

Lloyd, S.J. et al., 2021, First palaeointensity data from the Cryogenian and their potential implications for inner core nucleation age: *GJI* v. 226, p. 66–77. https://doi.org/10.1093/gji/ggab090

Insights into the structure of the Maltese Islands from new geological mapping

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The Maltese Islands are located on the Pelagian Platform, part of the African foreland, which is being subducted northwards beneath the Eurasian Plate. Early Miocene slab role-back of the African Plate resulted in the migration of the subduction trench and initiated extension of the Pelagian Block to the south of Sicily. The resulting N-S directed extension led to the formation of the orthogonal Pantelleria Rift and Malta Graben Systems. The Malta Graben System forms a series of ENE-WSW trending, syn- to post- deposition faults which form the major topographic structure of the Maltese Islands and locally controlled sedimentary facies distribution. The NW-SE trending Maglaq Fault, along the southwest coast of Malta, forms the northeastern margin of the Pantelleria Rift System and accommodated uplift of the Maltese Islands during the Pliocene – Present. Later dextral strike-slip movements have been documented on some faults in the Malta Graben System and associated deformation has resulted in the initiation of secondary faults within the graben system.

The British Geological Survey has recently completed remapping the Maltese Islands for the Maltese Government. The results show a complex history of active faulting during the Miocene – Present, with fault-controlled deposition, regional unconformities and depositional hiatuses. The revised mapping has enabled a better understanding of the fault kinematics and the temporal variation in fault movement. The new map, and accompanying field guide, will be published by the Maltese government to support development, hydrogeology and public outreach and incentivise investment and research on the islands.

Melt transport in the Götemar granite pluton

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Granitic plutons form in the ephemeral part of magmatic systems and can feed silicic volcanic eruptions. Concentric textural and chemical zoning in granitic plutons are often interpreted to reflect lateral expansion caused by centrally intruding magma. However, magma mush systems are thought to grow vertically by sill-stacking, the interplay between lateral expansion processes and melt transport within granitic mush systems therefore remains a focus of debate. This contribution investigates if the shape and structure of granite plutons assert control on the architecture of melt transport pathways in mushy magmas.

The Götemar pluton, Sweden, has a circular shape and consists of three major granite units, (i) coarse-grained, (ii) medium-grained, and (iii) microgranite. We employed mapping and Anisotropy of Magnetic Susceptibility (AMS) to examine melt transport pathways and strain patterns within the Götemar pluton. Sub-horizontal microgranite and medium-grained sheets that strike parallel to the pluton contact occur throughout the pluton (Fig. 1). The sheets pinch out toward the SE and show that the magma intruded from the NW. The AMS fabric is contact-parallel in the large medium grained granite body in the NW-part of the pluton, which suggest that the intruding melt caused inflation of the pluton. We propose that subsequent melt that intruded the granitic mush exploited concentric fractures that formed during inflation and were controlled by the instantaneous stress field in the coarse-grained granite magma to propagate into the mush. The Götemar pluton displays a clear link between concentric melt-transport within sheets and the coeval ambient stress field during emplacement.

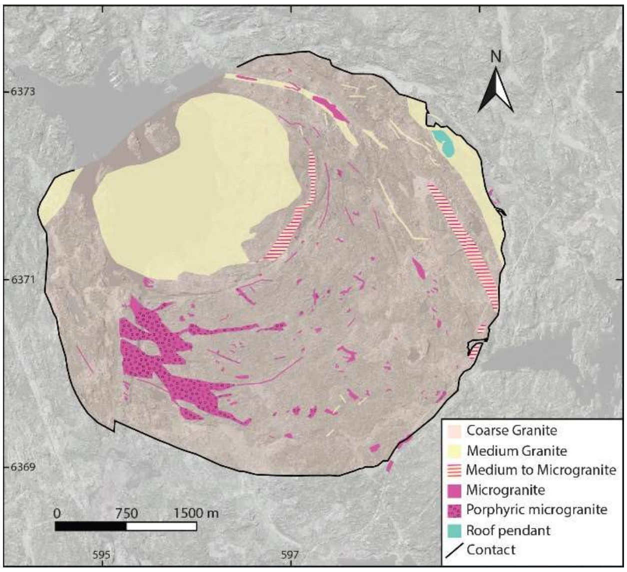

Figure 1. Map of the Götemar pluton overlaid on a satellite photo. Background: RGB-Orthophoto 0.25 m © Lantmäteriet (2017) and GSD-Elevation data, Grid 2+ © Lantmäteriet. Coordinate system: UTM 33N

Does the rain or the strain shape the mountain chain?

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Tectonics and climate combine to produce landscapes, but the relative contributions of each are not well understood. One issue is that tectonics and climate are not fully independent of each other, so that their relationships need to be considered. Another aspect is that tectonics, climate and landscape operate and are observed on different length-scales and timescales, making comparisons difficult. Here we analyze data for topography, precipitation and active strain rate for five active fold-and-thrust belts (Himalaya, Qilian Shan, Longmen Shan, Zagros and Andes), to understand the controls on landscapes in these regions. Topography is represented by the average of hypsometric integral (HI) and surface roughness (SR), measured over second order drainage basins. Strain rate magnitude is calculated from published geodetic data. All data are processed to give average values for each parameter for quadrats, drawn along each range. Each quadrat covers a region between the frontal thrust and the boundary with the internally-drained plateau in the hinterland. Comparing quadrat values, we find stronger correlations between precipitation and HI and SR (r^2 = 0.64 and 0.62 respectively), than between strain rate magnitude and HI and SR (r^2 = 0.38 and 0.51 respectively). Coupling between climate and tectonics is indicated by the positive correlation between precipitation and strain rate (r^2 = 0.55). This quantitative analysis allows us to conclude that climate is more important than active tectonics in shaping fold-and-thrust belt landscapes, at least for the parameters included in this study.

Posters
(in alphabetical order)

The relationship between thrusting and dyke emplacement: Insight from the Um Gheig thrust belt, Egyptian Nubian Shield (East African Orogen)

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The Um Gheig thrust belt in the Egyptian Nubian Shield developed during the late stage of the Pan-African Orogeny of the East African Orogen. The belt is characterized by imbricated stacks of massive amphibolite, heterogeneous amphibolites (interpreted as metavolcaniclastics) and ophiolitic metaultramafics, juxtaposed along NE-propagated thrust faults. The belt exhibits beautiful examples of fault propagation folds, duplex structures and backthrusts. Field relationships suggest that the Um Gheig thrust system was long-lived with shearing and thrust tectonics at decreasing metamorphic grade. The area is intruded by numerous felsic to mafic, 1 to 5 m thick dykes showing a variety of relationships to thrust related features. Many dykes are seen parallel to the thrust planes without any recorded shearing within the dykes themselves but clear high strain, low temperature shearing at dyke – host rock boundaries. This relationships suggest that the dykes utilised pre-existing weak thrust planes as pathways intruding during the late stage of thrusting. Other dykes are affected by open gentle folding, boudinage and small-scale thrust duplexes. Hence, these dykes intruded during the period of thrusting itself. Other dykes cut through all thrust related features clearly postdating the thrusting event.

Based on these field relationships, dykes can be used to constrain the timing of thrusting with implication not only for the local geology, but also for the timing of late stage deformation of the Egyptian Nubian Shield and the entire East African Orogen. In-depth studies of the sheared rocks promises to reveal PT conditions for thrusting along with potential possibility of direct dating of shear related minerals such as epidote.

FWI as a tool to predict fault zone properties: Samson Dome, SW Barents Sea

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Faults have variable permeability and thus play a major role in controlling subsurface fluid flow. Understanding the permeability conditions of fault zones has implications for locating water resources, hydrocarbons, mitigating seismic hazards and carbon capture and storage. However, calibrating and validating fault seal models is often an expensive endeavour that requires drilling multiple wellbores and collecting different datasets. Full-waveform inversion (FWI) is an advanced method of seismic imaging that aims to provide a high-resolution velocity model of the subsurface that utilises the full-waveform data from seismic surveys as opposed to the traditional velocity modelling workflows based on first-arrivals (Morgan et al., 2013 for more detail). The high-resolution capabilities of FWI can be used to highlight velocity differences of geological structures in the subsurface (i.e., intrusions, fluid escape features, etc.). Previous studies in subduction zones and sedimentary basins have qualitatively demonstrated the ability of FWI model to image fault zones with varying velocities relative to surrounding host rocks (e.g., Morgan et al., 2013; Gray et al., 2019).

In this study we investigate the potential of using FWI as a tool to predict fault zone properties using high-quality 3D seismic reflection depth migrated and FWI data from the Samson Dome, SW Barents Sea, offshore Norway. We mapped 14 horizons and c. 50 faults to describe the geometric and kinematic properties of the fault network. Then, we extracted the velocity values within the fault zones and compared them with the surrounding host rocks. Our initial results show velocity variations with the studied fault network with NW-striking faults having mainly lower velocity fault zones. This NW-direction is parallel to the orientation of the present-day maximum horizontal stress based on borehole breakout data (Heidback et al., 2016). Additional work is in progress to analyse the velocity variations further quantitatively and statistically between fault zones and host rocks in relation to the structural evolution of the Samson Dome and kinematic histories of the studied faults.

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The effect of human factors and measurement obliquity when extracting fault data from 3D seismic data.

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3D seismic reflection datasets are often used to interpret the evolution of complex normal fault networks. To do this, fault properties (e.g. throw and heave) needs to be extracted across several horizons, with data ideally collected orthogonal to the strike of the fault (ie parallel to inferred slip vector). The influence of subjective and objective uncertainties on the extraction of fault data is well studied; however, to date how measurement obliquity and human factors that influence the consistency of fault picks has gained little attention. We analyse data collected from four quasi-straight faults imaged in the 3D seismic survey. Using arbitrary lines constructed at varying obliquities (up to ±50˚), we statistically compare data extracted from an oblique sample line to that extracted from an optimally orientated sample line. Additionally, we analyse the difference between repeat picks across two horizons at each obliquity. We find statistically significant differences between repeat picks across all parameters for some, but not all datasets, with heave measurements particularly prone to large percentage differences. The effect of obliquity depends on the extracted fault property. For example, discontinuous throw shows low % differences across all obliquities (0 to 33%, $\bar{x} = 7\%$) and depends on the obliquity and fault cut-off gradients. Oblique transects sample an apparent dip causing heave, dip, and displacement extracted from oblique transects to display high percentage differences that increase with increasing obliquity (Fig 1). We suggest that measurement obliquity should not exceed 15˚, and where possible sample lines should be corrected to consider the local fault dip.

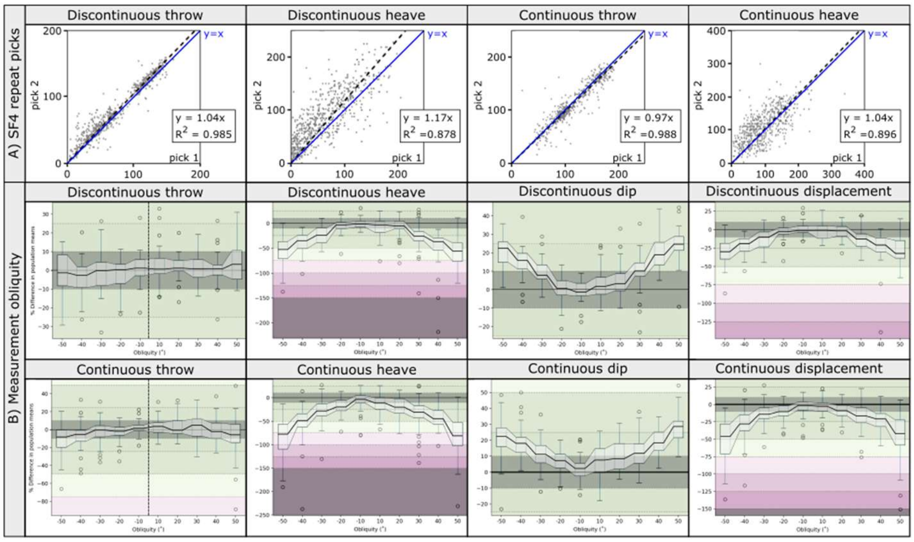

Figure 1: (a) Results from the repeat picks on SF4 and (b) normalised % difference between population means for key fault properties for all faults at different obliquities.

Signatures of dissolution-precipitation creep in the mid crust: an example from the Badcall shear zone, NW Scotland

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The processes that control deformation in the mid and lower crust are yet to be fully constrained, however, advances in analytical techniques mean we can re-visit previously studied areas to build upon understanding already gained. We conducted fieldwork and sampling along a 400m long transect spanning a mid-crustal Laxfordian-age (2300-1700 Ma) amphibolite-facies shear zone at Upper Badcall, NW Scotland, for which a strain profile already exists, to further investigate the hydration-strain-deformation mechanism relationship in the granulite-facies quartzofeldspathic gneiss host rock and cross-cutting 25m wide dolerite Scourie dyke. The gneiss and dyke are progressively rotated into the shear zone, towards which the proportion of high strain fabric increases and replacement of pre-existing pyroxene by hornblende+quartz and/or biotite in the gneiss and dyke goes hand in hand with change in mineral and whole-rock chemistry. These metamorphic reactions and chemistry changes indicate an increase in fluid availability towards the shear zone and successively decreasing temperature of deformation. Microstructural analyses reveal that initially reduced grain size, crystallographic and shape preferred orientation, and grain boundary alignment all increase towards the shear zone, without significant internal deformation of grains. At and within 100m of the shear zone, there are multiple variably deformed and undeformed quartz veins and 20-30% feldspar is lost in the dyke. Our results reveal a history of chemically-driven grain size reduction during pre-deformation metamorphic reactions, followed by dissolution-precipitation creep facilitated by localised availability of fluid along fractures. Thus, dissolution-precipitation creep weakens the mid crust through a dynamic interplay between fracturing, fluid influx and strain localisation.

A semi-automatic workflow for structural interpretation of large point-cloud Digital Outcrop Models on complex fractured metamorphic rocks (Aosta Valley, Italy)

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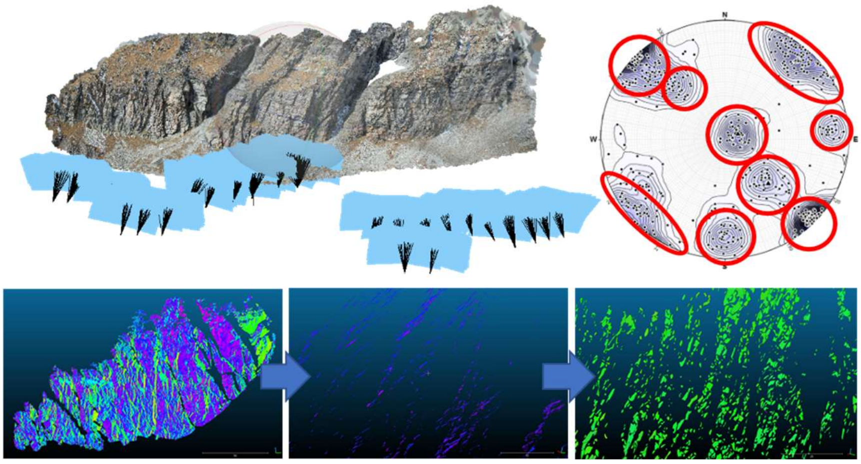
Characterization of fracture networks is essential for the analysis and modelling of mechanical and hydraulic properties of the rock mass. Here we present a study carried out in the context of the ReservAqua INTERREG project, on outcrops of fractured gneiss of the Dent-Blanche Nappe, exposed on the Italian side of the Cervino/Matterhorn in Valtournenche. Our methodology is based on a combination of traditional field surveys and remote-sensing techniques. The preliminary stage is represented by selecting outcrops that are representative in terms of structural and lithological properties of a larger rock volume. A field survey is carried out with traditional techniques, paying attention to the kinematics, relative chronology, and mineralization of structures. Simultaneously, remote-sensing datasets are collected. The result is a point cloud Digital Outcrop Model (DOM), colorized with RGB values, that should have a density (points/area) sufficient to characterize the smallest relevant structural features. From this, also textured surface DOMs and/or DEM plus orthophotos (for almost flat outcrops) can be obtained. The first step of DOM structural analysis is carried out "manually", selecting facets and traces with suitable software tools. This allows selecting different sets of structures, characterizing their orientation statistics, and assigning them to sets defined in the field. The second step consists in an automatic facets segmentation, using specific tools calibrated with results of the manual interpretation. Overall, this results in a supervised semi-automatic workflow, allowing to extract huge structural datasets in a reasonable time, maintaining the connection with kinematic and chronological observations carried out in the field.



Mirror-like surfaces in bituminous dolostones (Central Apennines, Italy)

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Mirror-like surfaces (MSs) are ultra-polished fault surfaces that reflect visible light thanks to their low surface roughness (nm-scale). Though common in nature, their formation mechanism is still debated: experiments show that MSs can develop both under seismic[1–4] and aseismic[5,6] deformation conditions, involving various deformation mechanisms operating over a broad range of P-T conditions, strain and strain rates.

To understand how MSs form, we studied 10 samples collected from normal faults cutting bituminous dolostones (Central Apennines, Italy). The MSs samples were from faults with increasing cumulated slip (from < 1 mm to few meters) and different resolved stress.

Microstructural investigations coupled with White Light Interferometry surface microroughness measurements reveal that the exposed mirrors: (1) consist of truncated dolomite clasts cemented by an ultra-thin layer (<1-2 μm) of nanoparticles and smeared bitumen and, (2) have RMS microroughness < 500 nm (over a lateral distance of few mm); however, the RMS decreases, and the mirror flattens with fault displacement. In the slip zone beneath, cataclasis and pressure solution, the latter associated to aseismic creep, are the main deformation mechanisms. Additionally, we conducted gas-chromatography on bitumen biomarkers from natural MSs, their wall rocks and from MSs obtained in the laboratory by shearing bituminous dolostones at seismic deformation conditions. Preliminary results show changes in the structure of biomarkers belonging to MSs, possibly a consequence of frictional heating during seismic slip. Therefore, the studied natural MSs may record both aseismic (i.e., pressure solution) and seismic (i.e., frictional heating) stages of the seismic cycle.

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Partitioning of fluid flow along faults and fractures in the Bristol Channel Basin

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This study addresses the topic of fluid flow along pre-existing faults and other fractures in the Bristol Channel Basin and the interplay between fluid flow and fault reactivation. U-Pb-t Thermochronology utilising LA-ICP-MS on fault related veins is used for the first time in this well studied basin to constrain the timing of initial fault development and subsequent-reactivation in the region.

Age data show that faulting has occurred in two significant stages. There is a period of extension from 150 – 120 Ma, followed by inversion from 50 – 20 Ma. Some structures such as the EastQuantoxhead Fault (EQHF) (fig.1) have veins that record more complex opening and mineral growth histories, suggesting that they have acted as conduits to fluid flow over repeated, discrete, episodes. Veins from the main EQHF yield ages ranging from ~150 Ma to ~29 Ma. Microtextural analysis, including EBSD shows evidence for multiple mineral growth and recrystallization (crystal plastic) events along the fault. Celestine is developed along the fault and represents one of the latest phases of mineral growth, including fibrous growth with reverse-sense kinematics.

Age data supported by other analysis has been able to confirm the timing of the main faulting events in the BCB, and detailed analysis of individual veins in the EQHF documents how this structure has evolved in the context of the wider basin. Changes to mineral phases, microstructure and the apparent mode of failure together indicate that the nature and extent of reactivation is strongly controlled by discrete fluids permeating along the fault core over a protracted period of time. Such changes suggest that the EQHF accesses different fluid sources over time, possibly through downward propagation of the fault through various units within the pre-Lias stratigraphy of the BCB.

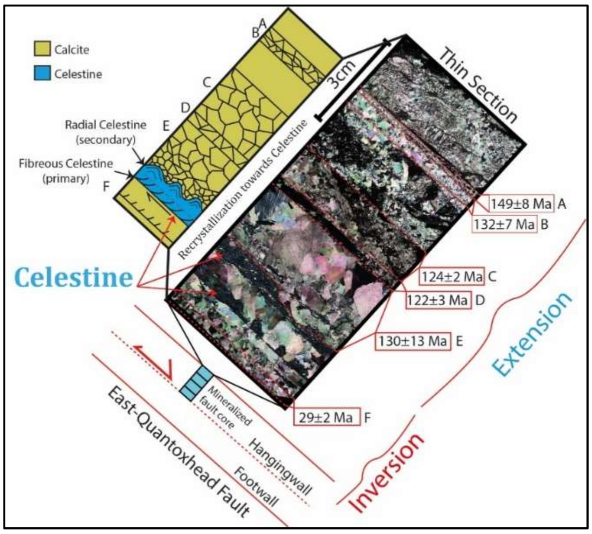

Figure 1: Age data of individual veins within the hanging-wall of the East-Quantoxhead Fault, as well as a schematic view of the different mineral phases.

The 155 km long intraplate, post-glacial, Pärvie fault, Sweden: Insights into stress transients triggering large intraplate earthquakes?

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Although plate tectonic theory successfully predicts that a vast majority of large earthquakes occur along plate boundaries, earthquakes exceeding M_w 6 also occur, albeit infrequently, in stable continental interiors. These intraplate earthquakes cluster in time and space, fitting poorly to a model of gradual accrual and release of elastic strain. Consequently, Caleis et al. (Geophysical Research Letters, 2016) proposed that intraplate seismicity is controlled by transient stress or strength perturbations in critically stressed crust. This paradigm needs testing – here we describe the structure of the major, postglacial Pärvie fault in the tectonically stable Fennoscandian Shield, to assess relations between fault geometry, stress field, and pre-existing structures during intraplate earthquakes.

The Pärvie fault is clearly marked in the landscape by an ≤ 25 m high, reverse-sense, fault scarp that is traceable for 155 km and trends NE-SW. The fault is currently microseismically active, and crosscuts glacial sediments related to the Weichselian icesheet. Similarly oriented faults with comparable late- to post-glacial timing are reported across the Fennoscandian shield. Radiocarbon dating of deformed material from trenched sections of the Stuoragurra fault, Norway, indicate that the post-glacial seismic activity may involve surface rupture as recently as 600 years BP, underlining the potential hazard importance of constraining the neotectonics history of these faults.

The rocks in which the Pärvie fault is hosted have a long history of Proterozoic to Recent deformation events, which highlights the possibility that this and other intraplate faults in continental shields are reactivating pre-existing basement shear zones and faults. Comparing and contrasting the fault zone geology in two locations highlights a localised fault that reactivates a phyllosilicate fabric where present and well-oriented, but cross-cutting stronger or poorly oriented fabrics.

If stable continental crust is critically stressed, then the relatively small stress perturbation caused by normal stress decrease during melting of the Weichselian icesheet may have been sufficient for faulting of intact crust. If this is the case, a large range of weak planes will necessarily also reach failure conditions. A possibility is therefore that a combination of intact crust at or near failure, plus potential for reactivating weak, pre-existing, chloritic shear zones where reasonably well oriented, can explain how a stress transient triggers a long rupture, of an immature fault, by linkage of new fault planes and reactivated faults and shear zones.

Melt patterns in migmatites: linking numerical experiments and field observations to understand rock-melt mixtures

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Partial melting and melt migration are common phenomena in rocks of the lower and middle crust and the presence of melt in these regions has important consequences on crust rheology and structure. After the onset of partial melting, the molten fraction can either flow towards shallower levels or remain where it formed. Once these rock-melt mixtures are "frozen in place" and brought to the Earth's surface, the geometrical distribution of this former melt can be used as an indicator of the rock's conditions at depth. These conditions include stress orientation, rates of deformation, local melt production and melt diffusion. The aim of this study is to quantify the role of such extrinsic and intrinsic parameters on geometrical patterns as this link is not yet well understood. We combine numerical simulations and field observations to interpret melt distribution in migmatites.

Our numerical simulations use an innovative hybrid model: pervasive percolation of melt is solved using porous flow and a network of springs on a second grid simulates the linear elastic behaviour of the host rock, including fracture formation and propagation.

We show how melt-filled fracture networks can develop from an area of partial melting and diffuse porous flow. These structures are essential for the onset of localised melt pathways which eventually evolve into larger melt channels. Our numerical experiments show how their spatial distribution is highly affected by the processes mentioned above. By combining relative rates of these parameters, we can define different regimes with specific melt pattern distributions, which can be used as a tool for the interpretation of a migmatite's history.

InSAR time-series of postseismic deformation on dip-slip faults

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The earthquake loading cycle is the repeated process of stress accumulation on a fault, and its subsequent release during earthquakes. Improved understanding of how strain evolves throughout the cycle in continental fault zones will allow us to have a better idea of their seismic hazard.

Previous studies have focussed on using geodesy, primarily GNSS & InSAR, to measure small fractions of the cycle of strain accumulation in major strike-slip fault zones, such as the North Anatolian and San Andreas Faults (Hussain et al., 2018), or on megathrusts (Ingleby et al., 2020). This observational bias towards larger faults is likely due to the large scale of the deformation, both in terms of spatial extent, and the measurable surface deformation.

However, there have been fewer studies on smaller earthquakes. Therefore, current understanding of mechanisms occurring during the seismic cycle, and fault structure at depth, is based on observations of major continental-scale faults, and may not be applicable to smaller faults, particularly those with dip-slip geometry (Ingleby and Wright, 2017).

The aim of my PhD is to study the seismic cycle on previously-overlooked continental dip-slip faults. With data from three generations of SAR satellites, we are currently constructing a 27-year time-series of postseismic deformation following the 1995 Mw 6.5 normal-faulting Grevena earthquake, Greece. In future, we will combine geodetic observations of dip-slip seismic cycle deformation in a range of global tectonic settings, with forward modelling, to constrain the structure of the fault, and assess the seismic hazard of dip-slip faults.

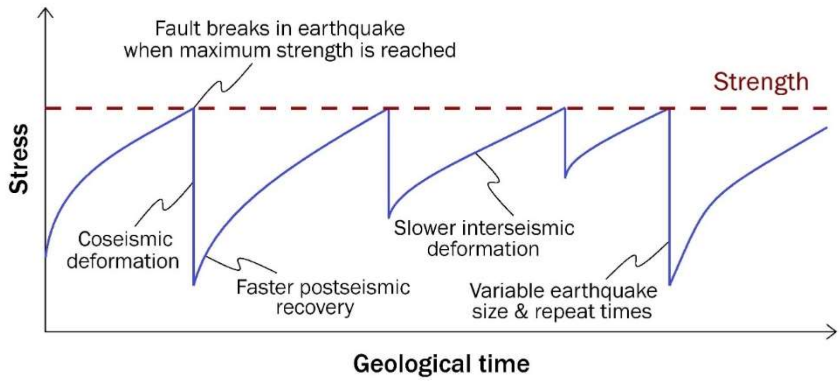

Figure: A conceptual graph of the evolution of stress over time on a fault, throughout the coseismic stress drop, postseismic and interseismic periods of the earthquake cycle. Adapted from Kanamori & Brodsky (2004).

Basement rheology influenced rift evolution in the North Taranaki Basin, New Zealand

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Rift morphology and kinematics are influenced by crustal rheology and architecture. The Taranaki Basin is an offshore rift basin off the west coast of the Northern Island of New Zealand. The Taranaki Rift system evolved as a multi-phase rift in highly heterogeneous crust composed of several basement terranes of varying strength which were accreted during the Mesozoic. These terranes contain numerous inherited structures formed before and during terrane accretion. While the concept of structural inheritance is well understood, the degree of reactivation of inherited structures across varying basement terranes is poorly constrained. Here we use high-quality 2D and 3D seismic data to investigate how the basement geology influences the rift architecture. We found that areas of weaker crustal rheology repeatedly accommodated strain during the multi-phase evolution of the Taranaki Rift. Our results show that areas of weak crustal rheology may result in more complex rift basins with more densely spaced faults, while areas of stronger rheology might develop fewer faults that are more influenced by discrete inherited fabrics. Rifting across different basement terranes is common in many basins across the globe, therefore these results are applicable to numerous rift systems such as the East African Rift System, the Labrador Sea or the Campos Basin, offshore Brazil.

Estimating the depth extent of suface rupturing creep events along the Central San Andreas Fault

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Surface creep on the San Andreas Fault was first identified in the 1960s (Steinbrugge et al., 1960) and has been observed to occur in bursts of slip known as creep events (e.g., Gladwin et al., 1994). Despite knowing about these creep events for 50+ years, there is still no consensus on the rupture extent of these events, with previous estimates suggesting one of three scenarios: short and shallow (e.g., Goulty and Gilman, 1978), long and shallow (e.g., Slater and Burford, 1979), or long and deep (e.g., Bilham et al., 2016). In this work, we use strainmeter and creepmeter data to try and constrain the rupture extent of creep events.

Using the creep event catalogue of Gittins and Hawthorne (2022), we identified strain events associated with creep events at the northern end of the creeping section using PBO strainmeter data. We model these strain events as rectangles of slip (Okada, 1985, 1992), varying the width and length of the rectangular patch as well as its depth, location on the fault, and the magnitude of the slip event. Here we present the model results for the three creep event scenarios along with slip probability distributions for events that are observed at the northern end of the San Andreas Fault.

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Quantifying Holocene fault slip rates in SW Turkey: results from cosmogenic nuclide analyses on bedrock fault scarps

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**Now at: MS Amlin

In zones of distributed continental faulting, it is critical to understand how slip is partitioned onto brittle structures. Measuring earthquake slip histories on long (millennial) timescales is challenging due to earthquake repeat-times being longer or similar to historical earthquake records, and a paucity of data on fault activity covering millennial to Quaternary scales in detail. Cosmogenic isotope analyses from bedrock fault scarps have the potential to bridge the gap, as these datasets track the exposure of fault planes due to earthquakes with millennial resolution. In this presentation, we show ^{36}Cl data from three neighbouring faults to quantify how strain is shared across the Muğla-Yatağan basin in SW Turkey, which experiences back-arc extension related to the convergence of Asia-Africa.

The concentration of ^{36}Cl measured on a fault plane reflects the rate and patterns of earthquake slip over the Holocene. We use Bayesian modelling techniques to estimate slip histories based on cosmogenic data from the Muğla, Yatağan, and Yılanı faults. The data are consistent with continued exposure of the fault planes over the Holocene. We find that the results from all faults are well modelled with a mostly constant slip rate over time that ranges from ~0.2–07 mm/yr across the different sites, though the best fitting modelled slip histories include a recent reduction in slip rate at all three sites. We suggest that the faults might host earthquakes around the same time, working together to share the strain across this major basin, and that there might be a recent slip deficit.

Deformation Microstructures in quartz of peak-ring granitoids of the Chicxulub Impact Crater

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Large impact craters possess topographic ring structures internal to the crater rim called peak rings. Current models of peak-ring formation involve collapse of a central uplift outwards over the collapsed transient crater rim, contributing to a complex spatial and temporal distribution of strain in peak-ring material. Testing this model against direct observations is difficult due to the extreme conditions and complex deformations involved. The ca. 66 Ma Chicxulub crater, located on the Yucatán peninsula of Mexico, is a ~200 km diameter peak-ring crater that was recently drilled by IODP-ICDP Expedition 364. In this study we aim to constrain the mechanics of peak-ring formation.

Previous work has focussed on brittle deformation structures and the orientations of specific crystallographic deformation features such as kinked biotites, and shock effects in quartz. Here, we compare crystal-plastic deformation in quartz from peak-ring granitoids with previously identified deformation and numerical impact simulations that track different phases of deformation. Using Electron Backscatter Diffraction (EBSD) analysis of shocked quartz, we show that the misorientation axes of subgrain boundaries are dominantly parallel to c, a, and m directions. The majority of samples possess a single dominant spatial axis of misorientation which varies in orientation with depth in the peak ring, with some samples showing a girdle of misorientation axes. Considering these observations in the context of depth, previous literature, and numerical impact simulations, we hope to constrain the kinematics of large crater formation, and quantify the contribution of crystal-plastic deformation to the total strain accumulated during impact cratering.

Characterizing fracture systems and their connectivity from the frontal exposure of a major thrust: Insights from Ramgarh thrust, Eastern Himalaya, Sikkim

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Frontal exposures of major thrust faults in orogenic wedges record quasi-frictional deformation due to faults cutting-up stratigraphic sections and concomitant erosion. We examine deformation signatures from the frontal-most exposure of a major thrust, the Ramgarh thrust (RT), from Sikkim Himalaya to understand how shallow-crustal deformation gets localized in fault zones. Being the roof thrust of a major duplex, RT has undergone reactivation and recorded long deformation history.

The RT zone is ~57m thick near Setikhola (N26°56.178’, E88°26.607’), exposing interfoliated Daling quartzite and phyllite, and is intensely fractured. The bedding-cleavage relationship indicates that RT zone lies in the overturned forelimb of a fault-bend antiform. We characterized the fractures based on the angular relationship with the bedding. High-angle fractures (60º-90º; ~41. 55%) are the most dominant, followed by moderate-angle (30º-60º; ~37.01%) and low-angle fractures (<30º; ~21.42%). Approximately 31% of the total fractures preserve genetic signatures on their exposed surfaces, with ~27% shear fractures (slickenlines) and ~4% extension fractures (plumose). Thus, shear fracture surfaces are better exposed than extension fractures. Shear fractures are dominantly low- (~36%) and moderate-angle (~41%) fractures, whereas extension fractures are dominantly high-angle (~66%). High-angle fractures record maximum fracture intensity, followed by moderate-angle and low-angle fractures. Preliminary analysis suggests that lithology controls fracture distribution more effectively than structural distance in the RT zone. Despite high fracture frequency, crosscutting nodes (~7.57%) are less abundant, indicating poor fracture connectivity. Extension fractures make more isolated nodes, whereas shear fractures record higher crosscutting nodes. Shear fractures contribute more towards fracture connectivity than extension fractures.

Making use of Fault Orientation in Deep Learning Models applied to 3D seismic data

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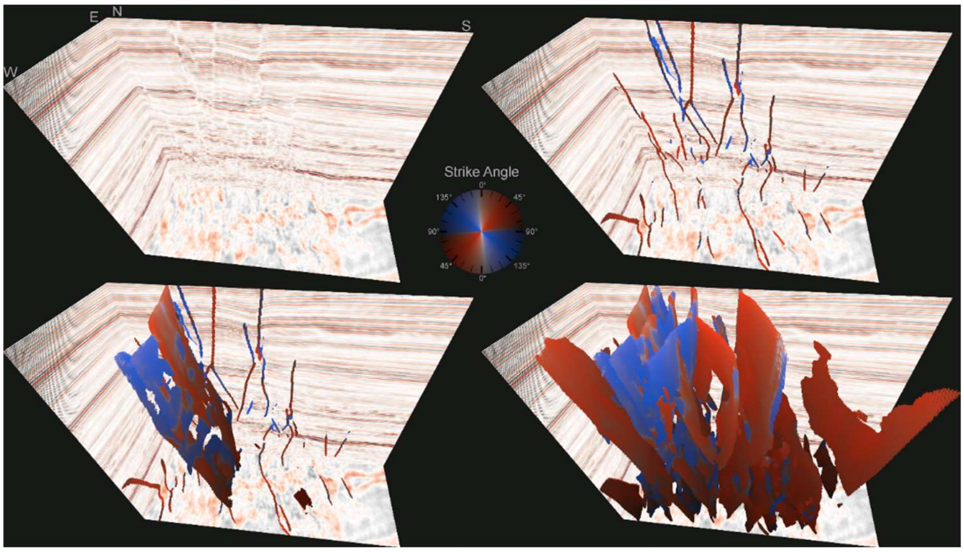
We can represent the orientation of a plane in 3D by its normal vector. However, every plane has two normal vectors that are negatives of each other. We propose four novel representations of vectors in 3D that are negation invariant and can be used by a neural network to predict orientation. To the best of our knowledge, our proposed solution is the first to introduce representations that are negation invariant, continuous and easily parallelisable on the GPU. We evaluate the representations by predicting the orientation of a plane on a toy task, and by applying them to synthetic seismic tomographic data where we predict the presence and orientation of faults for every voxel in the volume. We further make use of the orientation of the faults in a post-processing algorithm on the GPU that separates the faults into segments (i.e. instances) that do not intersect, which allows us to selectively visualise faults in 3D. We demonstrate the utility of the representations by deploying the model on the Laminaria 3D Seismic volume as a case study. We quantitatively compare the model's prediction against human interpretations of slices through the volume as well as existing interpretations in literature. Our analysis shows that the model shows good agreement with human interpretation in the shallow levels, where the ambient noise is lower, but agreement between model and interpreter degrades at deeper levels. We explore possible reasons for this lack of agreement.



TL– uninterpreted seismic, TR – fault traces picked by the deep learning algorithm
BL – A single fault visualised in 3D – colours relate to orientation, BR – all faults visualised

Strain archives of enclaves and its correlation to rheological conditions: a magnetic and petrographic analysis

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Studying tectonic processes within igneous bodies is dependent on their archiving of palaeostress. Strain partitioning within intrusions is reliant on a magma's effective viscosity, with rheological transitions (e.g., crystal volume surpassing 60%) controlling strain distribution and mechanical behaviour. Rheological transitions can be investigated where contrasting magmas interact, such as at magma mingling zones. Contradictory models of strain partitioning between enclaves and host magma during cooling are currently hypothesised, two leading models are that 1) enclaves transition from strain indicators to passive markers beyond a rheological threshold (Caricchi et al. 2012) and 2) continuous partitioning of strain throughout crystallisation via development of mush-state force chains within enclaves (Burgisser et al. 2020).

The Fanad Pluton, NW Ireland offers an opportunity to test the feasibility of both hypotheses with exposed, variably aligned, enclaves occurring within this foliated monzodioritic pluton. The pluton archives a subvertical NE-SW petrofabric, with two enclaves and the surrounding monzodiorite sampled along a cm-scale grid for this study. One enclave is aligned parallel to the petrofabric, the second misaligned NNW-SSE. Anisotropy of Magnetic Susceptibility (AMS) was analysed in the enclaves and monzodiorite to compare their magnetic fabrics and the monzodiorite petrofabric. Results show magnetic fabrics in both enclaves align with the magnetic and petrofabrics of the host, implying a cohesive strain archive between both magmas independent of the rheology contrasts. However, Anisotropy of Magnetic Remanence which isolates the fabric of ferromagnetic particles, reveals a petrofabric-oblique subfabric within both enclaves. This suggests multiple minerals control the AMS fabric, requiring further analysis.

Burgisser, A., Carrara, A. and Annen, C., 2020. Numerical simulations of magmatic enclave deformation. *Journal of Volcanology and Geothermal Research*, 392. https://doi.org/10.1016/j.jvolgeores.2020.106790.
Caricchi, L., Annen, C., Rust, A. and Blundy, J., 2012. Insights into the mechanisms and timescales of pluton assembly from deformation patterns of mafic enclaves. *Journal of Geophysical Research B: Solid Earth*, 117(11). https://doi.org/10.1029/2012JB009325.

Post-Messinian tectonics of the Apulian Plateau offshore Capo Santa Maria di Leuca (Southern Italy)

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The Apulian Plateau (Southern Italy, offshore Capo Santa Maria di Leuca) represents the foreland and possibly the forebulge of the Hellenides and Southern Apennines, however it is still poorly investigated; this has stimulated an in-depth study of its progressive tectonic deformation, recorded in the Miocene and particularly Plio-Quaternary succession.

We integrated high-quality reprocessed 2D seismics, a few exploration wells and high-resolution bathymetries in a large scale 3D modelling project. The interpretation on seismic profiles revealed a dense network of normal faults dipping towards the SW and NE. Larger offsets are observed on structures facing the Apennines' Bradanic foredeep. Statistical analysis of fault sticks highlights a large family of structures with apparent heights up to 600 msec, sealed by the 770 ka unconformity. Larger faults that can be correlated over several seismic lines show heights of up to 1800 msec and reach the Cretaceous platform at depth. Some of these larger faults extend to the sea bottom, where they are marked by well defined fault scarps in the bathymetry.

In this contribution we will address the age of faulting and the offsets and total horizontal strain accumulated in time.

A Structural Analysis of the Layered Kakortokites within the Ilímaussaq Complex, South Greenland

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The Ilímaussaq Complex (1160 Ma), South Greenland, displays spectacular igneous layering and contains a world-class REE deposit [1]. This study presents novel structural data from the layered kakortokite Units -1, 0, +1 and +2, to assess the preserved rock fabric record and test its compatibility with previously proposed igneous layering mechanisms. Detailed stratigraphic log sections are presented alongside Anisotropy of Magnetic Susceptibility (AMS) results from 198 samples that reflect the textural and rock fabric characteristics of Unit 0. AMS is a powerful tool as it can measure rock fabrics that are invisible to the naked eye, providing an important set of structural data typically difficult to collect from igneous intrusions in the field. Preliminary AMS results record the highest mean magnetic susceptibility values (K_{mean}) at the base of each Unit. Shape factor (T_j) values return a prolate tensor shape in 77% of sample sites, which reflects the presence of a previously unrecognised, prominent mineral lineation in this layered intrusion. Our results also show a progressive change of the magnetic lineation orientation from the base towards the top of Unit 0. Critically, both AMS fabrics and field observed alkali feldspar foliations are oblique to the modal layering of the kakortokites. These data indicate that at least two magmatic processes occurred at Ilímaussaq: one responsible for the alignment of alkali feldspar, and another which formed the modal layering. This study shows how structural data can further our recording of igneous processes which occur sequentially during the crystallization of intrusions.

Sørensen H (2001) Geology of Greenland Survey Bulletin 190:7-23

Intrusion-induced forced folds and fractures

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Space for magma is often created by uplift of the overburden and free surface, producing a forced fold. These forced folds are non-developable, dome-shaped or flat-topped, four-way dip closures the geometry and size of which broadly reflects that of the underlying intrusion. It is critical to understand how these forced folds develop because: (1) their growth drives the ground movement that often heralds volcanic eruptions; and (2) they form ideal structural traps for sub-surface fluids. Previous studies have examined the geometry and amplitude of such forced folds in relation to the intrusions that create them, but few have quantified the fracture patterns prevalent throughout them. These fractures are created by radial and circumferential extension across the folded surfaces as they are uplifted. Here I use remote sensing data to map fracture patterns across intrusion-induced forced folds that are natural (e.g. in the Danakil Depression, Ethiopia) and those created in published physical models. Using FracPaq to quantify fracture sets, I look at how fractures develop and connect through time, and relate to forced fold geometry. With these data I hope to establish how we can predict forced fold fracture patterns in the sub-surface.

Structural Asymmetry and Shock Metamorphism as Indicators of Impact Obliquity at the Gosses Bluff Impact Crater

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More than half of impact cratering events occur with impact obliquities between 30° and 60°, yet the effect of obliquity on crater structure remains poorly understood. On other planets, impact angle is commonly inferred from impact ejecta distribution, but since this ejecta is rarely preserved on Earth, other observations must be used. The ~24km diameter Gosses Bluff impact structure in Northern Territory, Australia, dated at ~142 Ma, has an asymmetric, outcropping central peak with 3.2km of structural uplift, while the rim of the structure is poorly preserved. In this study, we aim to constrain the angle of impact at this site by combining observations of asymmetries in shock metamorphism and crater structure with the results of numerical impact simulations. We measured planar deformation features in shocked quartz from samples around the bluff, features which are a proxy for peak shock pressure. We find that there is a systematic variation in peak shock conditions around the bluff, ranging between ~8-16 GPa, which is consistent with the asymmetry of the crater and implies an oblique impact. We use the iSALE shock physics code to simulate the impact event to match the structural observations by varying impactor size, material strength and porosity, and will soon expand this to include impact angle. Ultimately, this study aims to quantify the obliquity of the Gosses Bluff impact as well as generate a useful set of criteria for constraining impact obliquity in terrestrial impact structures.

Deciphering laccolith growth with palaeomagnetism

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Palaeomagnetic vectors associated with magmatic intrusions are locked in during cooling of the magma. If the magma is rotated after the palaeomagnetic vector has been locked in, the rotated vector represents a passive marker of deformation. The silicic 11.2 Ma Sandfell laccolith in Iceland displays evidence of early sill emplacement and subsequent deflection and brecciation of the magma (Mattsson et al., 2018). Combining a novel palaeomagnetic baked contact test with incremental fold tests, Twomey et al. (2021) demonstrated that palaeomagnetic back-stripping effectively constrain intrusion-induced forced folding in the host rocks at Sandfell. Here, we advance this work by testing the feasibility of using palaeomagnetic transects within the laccolith to assess the inflation mechanism at different stages of laccolith emplacement.

Samples were primarily collected along a 150-metre vertical transect from the laccolith roof through the centre of the Sandfell laccolith along a normal fault scarp. Three clusters of palaeomagnetic vectors can be identified amongst the sample sites. Cluster A (sites located <30 and >100 m below the roof) yield a mean vector of D=167°, I=-70° (N=14, a95=5.4°). Cluster B (sites located >30 and <100 m below the roof) has a mean vector of D=179°, I=-40° (N=9, a95=8.6°). Cluster C displays a mean vector of D=243°, I=-82° (N=6, a95=8°) and overlap with the expected palaeomagnetic vector of the area at 11.2 Ma. The spatial link between the compiled sites and the palaeomagnetic vectors show that the vectors were locked in soon after emplacement and were rotated during progressive stages of laccolith growth.

Mattsson, T., Burchardt, S., Almqvist, B.S.G., Ronchin, E., 2018. Syn-Emplacement Fracturing in the Sandfell Laccolith, Eastern Iceland—Implications for Rhyolite Intrusion Growth and Volcanic Hazards. Frontiers in Earth Science 6, 5. https://doi.org/10.3389/feart.2018.00005
Twomey, V., McCarthy, W., Magee, C., Petronis, M., and Mattsson, T.: Unravelling the dynamics of magma emplacement through palaeomagnetic backstripping of intrusion-induced host rock deformation: Analysis from the Sandfell Laccolith, SE Iceland, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-15561, https://doi.org/10.5194/egusphere-egu21-15561, 2021.

A modelled case for dissolution precipitation in the Southern Alps, New Zealand

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The Southern Alps, New Zealand, forms the part of the onshore expression of the Australian and Pacific plate boundary, due to uplift following oblique slip along the inclined Alpine Fault.

Of the ~40 mm/yr of Pacific plate motion, only 80-90% is accommodated by fault slip, with the remaining ~5% attributed to internal deformation of the Southern Alps, most commonly associated with mylonitisation near to the fault, and the development of back-shears as crustal material from 30—35 km depth along the Alpine Fault ramp. However, here we present the case for dissolution precipitation being another, often overlooked deformation mechanism in this region.

There is extensive geophysical evidence for the presence of large quantities of fluid at the base of the Southern Alps (e.g. large conductivity anomalies in magnetotelluric surveys, and seismic low velocity zones). Additionally, the preservation of high densities of quartz fractures at surface exposures indicates the precipitation of large quantities of dissolved material.

Extensive monitoring of ground motions and uplift rates, and modelling of the spatial distribution of exhumation rates, means that we are able to back-project the exhumation paths of heavily fractured surface outcrops through extensive catalogues of micro-seismicity in this region. By comparing our forecasted fracture density to those seen at the surface, we find that there are more fractures observed at the surface than can be explained without the re-distribution of host rock material by dissolution, and that therefore dissolution precipitation is an under-appreciated deformation in the exhumation of crustal material in this region.

From large scale to small scale: The tectonic environment and microstructural characteristics of gold-bearing quartz veins at Croagh Patrick, Ireland

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Croagh Patrick, Ireland, is a well-studied Appalachian-Caledonian orogenic gold deposit, with gold mineralisation within two quartz vein generations (A- and C- veins). Past research suggests based on petrography that these veins formed synchronously with five quartz formation phases with the last phases introducing gold.

However, it could be argued the veins have distinctly different deformation histories as the A vein shows a different and much stronger folding pattern compared to the C vein. Additionally, SEM-EDS work has identified that A vein precipitates arsenopyrite and other minor sulphides, while these are absent in the C vein. A-vein gold content also contains a higher silver content than C veins.

Here we use quantitative microstructural analysis through EBSD which is sparsely used within ore deposit research, to determine potential post-mineralisation processes causing these petrographic differences.

First results highlight a clear heterogeneity of strain localisation within the A vein. Quartz within regions without arsenopyrite have smaller crystal sizes compared to areas with arsenopyrite and/or gold. These small crystal sizes also have very high concentrations of dauphiné twinning and a strong local CPO indicating grain size reduction via dislocation creep at greenshist facies conditions. Quartz with arsenopyrite have large crystal sizes and no apparent crystal lattice deformation or recrystallization textures suggesting post deformation fluid influx and crystallization. However, cathodoluminescence interpretation is required to concretely conclude this. Our first observations suggest that the deformation-fluid infiltration and ore generation history and structural framework within these veins is more complex than what might have previously been thought.

How have thick evaporites affected early sea-floor spreading magnetic anomalies in the Central Red Sea?

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The axial region of the Central Red Sea has been shown to be floored by oceanic crust, but this leaves the low amplitudes of off-axis magnetic anomalies to be explained. Furthermore, if seafloor spreading occurred in the late Miocene, it is unclear how that occurred as widespread evaporites were being deposited then and may have covered the spreading centre. In this study, we derive crustal magnetization for a constant-thickness source layer within the uppermost basement by inverting aeromagnetic anomalies using basement depths derived from seismic reflection and gravity data. Peak-to-trough variations in magnetization away from the axis are found to be slightly less than half of those of normal oceanic crust, but not greatly diminished, and hence the magnetic anomalies are mostly reduced by the greater depth of basement, which is depressed by isostatic loading by the evaporites (kilometres in thickness in places). There is no relationship between seafloor spreading anomalies and the modern distribution of evaporites mapped out using multi-beam sonar data; magnetizations are still significant even where the basement lies several kilometres under the evaporites. This suggests that magnetizations have not been more greatly affected by alteration under the evaporites than typically exposed oceanic crust. A prominent magnetization peak commonly occurs at 60-80 km from the axis on both tectonic plates, coinciding with a basement low suggested previously to mark the transition to continental crust closer to the coasts. We suggest an initial burst of volcanism occurred at Chron 5 (at ~10 Ma) to produce this feature. Furthermore, an abrupt change is found at ~5 Ma from low-frequency anomalies off-axis to high-frequency anomalies towards the present axis. This potentially represents the stage at which buried spreading centres became exposed. In this interpretation, intrusions such as sills at the buried spreading centre led to broad magnetic anomalies, whereas the later exposure of the spreading centre led to a more typical development of crustal magnetization by rapid cooling of extrusives. However, the results suggest that the magnetic anomalies at ocean-continent boundaries in general may be more complicated than originally thought, depending on the local importance of sediment cover.

Okwokwo, O. I., Mitchell, N. C., Shi, W., Stewart, I. C. & Izzeldin, A. Y. (2022). How have thick evaporites affected early seafloor spreading magnetic anomalies in the Central Red Sea? Geophys. J. Int., 229, 1550–1566. DOI: 10.1093/gji/ggac012

The November 9, 2022, compressional seismic sequence (Mw 5.5)-another piece of information to the 3D seismotectonic fault model of the coastal Marche-Adriatic offshore area (Italy)

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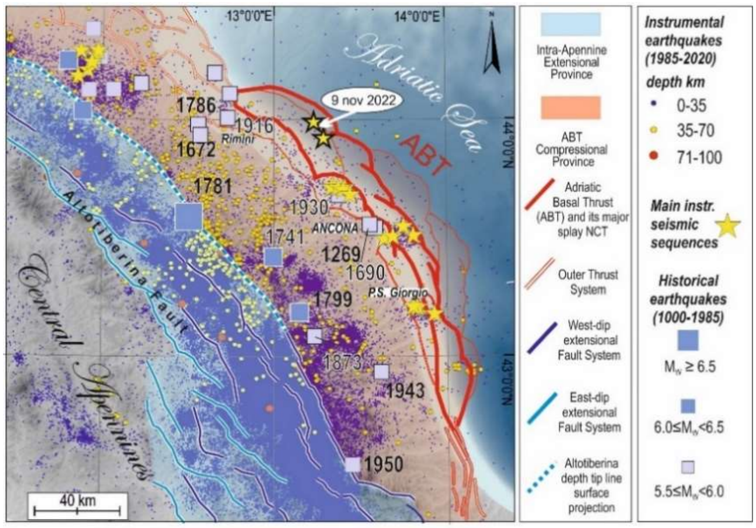
The coastal Marche-Adriatic region of eastern-Central Italy has been long questioned in the literature whether being active or not and, in case of activity, whether under a compressional or a strike-slip regime (de Nardis et al., 2022 with references). Our recent paper integrates high-quality seismological data from a local network with long-term geological constraints to build a 3D crust-scale seismotectonic fault model. Late Pliocene-to-Quaternary NE-verging fold-and-thrust structures develops at the hangingwall of the Adriatic Basal Thrust (ABT), a SW-dipping reverse shear zones which penetrate across the entire crust and is seismogenic at upper and lower crust depths.

The November 9, 2022 seismic sequence activated one offshore ABT upper crustal splay with pure compressional kinematics. Two major events (M_W 5.5 and 5.2) enucleated within 1 minute, at depths of ~5 km and ~7.5 km, respectively, and ~8 km away in map view. At a depth of a few kilometres, the seismogenic thrust intercepts two deep extraction wells (Pesaro Mare 4 and Bice 1), re-opening the question of triggered and induced seismicity. Geological section, serial hypocentral cross-sections, focal mechanisms, and available information from exploration wells are used to build a detailed nonplanar 3D geometric and kinematic fault model of the structures responsible for the sequence and to test its fits with the previously built regional model. Preliminary observations highlight a synchronous activity of the upper crust segment activated by the sequence with that of surrounding multi-depth fault structures, and Coulomb stress scenarios are built for analysing such an aspect.



De Nardis et al. (2022) Lithospheric double shear zone unveiled by microseismicity in a region of slow deformation. Accepted for publication on Scientific Report

The effect of breached relay ramps on early post-rift sedimentary systems

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Fault relay ramps are important sediment delivery points along rift margins and provide flow pathways in deepwater sedimentary basins. They form as tilted rock volumes between en-echelon fault segments, which become modified through progressive deformation, and may develop through-going faults that 'breach' the relay ramp. It is well established that hinterland drainage (fluvial/alluvial systems) is greatly affected by relay ramps at basin margins. However, the impact on deepwater (deep-marine/lacustrine) subaqueous sedimentary systems, particularly by breached relay ramps, is less well documented. To better understand these breached relay settings, this study examines a suite of high-quality subsurface data from the Early Cretaceous deep-lacustrine North Falkland Basin. The Isobel Embayment breached relay-ramp, an ideal example, formed during the syn-rift and was later covered by a thick transitional and early post-rift succession. Major early post-rift fan systems are observed to have consistently entered the basin at the breached relay location, directed through a significant palaeo-bathymetric low associated with the lower, abandoned ramp of the structure. More minor systems entered the basin across the structure-bounding fault to the north. Reactivation of basin-bounding faults is shown by the introduction of new point sources along its extent. This study shows the prolonged influence of breached relay ramps on sedimentary systems into the early post-rift phase. It suggests that these structures can become reactivated during post-rift times, providing continued control on deposition and sourcing of overlying sedimentary systems. Further characterising the likely sandstone distribution in these settings is important as these systems often form attractive hydrocarbon reservoirs.

Quantitative relationships between fault kinematics and glacial processes

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The fluvio-glacial Quaternary sands and gravels exposed near Lleiniog (Anglesey, North Wales) have been deformed by several different mechanisms including faulting [1, 2]. Based on the offset of bedding and sedimentary structures Lee *et al*. (2015) identified both normal and reverse faults. During recent fieldwork at Lleiniog the orientations of faults were supplemented with detailed measurements of bedding and laminations in the immediate vicinity of the fault surfaces.

The aim of this work is to directly relate the results of detailed geometric and kinematic analyses of these faults to sub - and pro - glacial processes. Based on current fault dips and fault cut - off angles (i.e. the angle between a fault and bedding) two, possibly three, families of faults can be identified. These faults are characterised by either:

(a) low dips and moderate cut - off angles;
(b) moderate dips and moderate cut - off angles;
(c) steep dips and large cut - off angles.

The kinematics of the three geometries have been modelled assuming that the fault blocks are rigid bodies, the so called rigid domino model of faulting. Within these blocks fault cut - off angles are preserved and movement along the faults must be accompanied by rotation of the faults and fault blocks themselves.

Initial results from this modelling indicate that there are faults that display high to moderate amounts of rotation as well as faults with limited to no rotation. Greater amounts of rotation are associated with greater amounts of horizontal extension or contraction, possibly linked to subglacial processes. High angle faults with small amounts of rotation are most likely to be a consequence of vertical collapse features with little or no translation, possibly formed in a pro - glacial setting. Quantitative modelling of the type presented here may provide new insights into ice sheet dynamics, unrestricted by the age or geographic location of the deposits. Comparisons are drawn with small-scale faulting below largely rigid thrust sheets.

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[2] Lee, J.R., Wakefield, O.J.W., Phillips, E., Hughes, L., 2015. Sedimentary and structural evolution of a relict subglacial to subaerial drainage system and its hydrogeological implications: An example from Anglesey, north Wales, UK. Quaternary Science Reviews, 109, 88 - 110.

Rate-dependent strength and the scaling of impact craters

[1*]Auriol S. P. Rae, [2]T. Kenkmann, [3]G. S. Collins, [2]M. Poelchau, [4]V. Padmanabha, [5]F. Schäfer

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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 10^1 to 10^2 s^{-1}, is rate-sensitive. Typically, rocks are stronger when deformed at high strain-rate conditions. 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 of the target material. Dynamic compressive strength and fragmentation in brittle materials is not currently implemented in numerical impact simulations.

In this study, we use the results of high strain rate 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 of large craters where strength is less important. Our rate-dependent strength model is an important development due to the need to accurately ground-truth numerical impact models against laboratory scale experiments, showing that laboratory measured strength values can be directly used as inputs for constitutive models in numerical impact simulations.

Is there an isotopic signature to co-seismic deformation? An investigation

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Microstructural, mineralogical, and mechanical signatures are frequently implemented investigatory methods to understanding coseismic deformation within natural and synthetic settings. Preliminary work indicates interactions between pore-fluid and fault rocks during and after seismic slip may be traced by distinct isotopic signatures and have potential to be implemented as a tool for investigating seismic cycle processes. Natural samples from the Alpine Fault (AF), New Zealand display high heavy oxygen isotope ratios within principal slip zones (PSZs). This signature may result from 1) grain comminution and subsequent increased surface area and frictional heat generation enabling kinetically unfavourable fluid-mineral reactions; 2) the flow of exotic fluids focussed along PSZs during seismic pumping; 3) thermo-mechanical release of mineral-bound water and local reincorporation of these ^{18}O enriched fluids in secondary mineral phases precipitated post seismically. During experiments shearing mineralogically representative synthetic gouge in contact with isotopically doped, equilibrated hydrothermal fluids, the oxygen isotope signatures of resulting fault gouge indicate that fluid-rock interaction driven by shearing has occurred, even during short term experiments (hours). This suggests mechanically driven fluid-rock interaction processes can be traced isotopically. In these experiments, we observe no mechanical healing in previously unsheared gouge, but gouge that experienced a prior high velocity pulse had contrasting results and healed as expected, indicating that fluid-rock interaction controls on healing are related to lower average grainsize and co-seismic production of strain hardening minerals. Future work will focus on identifying the process driving these mechanical and isotopic signatures.

The impact of competence contrast on normal fault dip-linkage

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Competence contrasts are crucial in controlling fault geometry and localisation in multilayer sequences. Due to rheological differences in multilayers, vertical fault segmentation is common in normal fault systems. In this context, a better understanding of the relationship between mechanical stratigraphy and vertical fault segmentation is crucial to improving interpretation accuracy. This work explores the influence of rheology on vertical fault segmentation using photogrammetry of a cliff section with excellent fault exposures located in the Costa di Calafuria, Italy. We provide a qualitative and quantitative characterisation of a multilayer layer sequence and analyse the impact of mechanical stratigraphy on normal faulting dip linkage. More accurate fault interpretations are crucial to develop more accurate structural models which are crucial on fluid migration, reservoir characterisation and integrity of geostorage sites.

Proterozoic Supercontinent Nuna in a Quadrupolar Framework

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Supercontinent Nuna assembled through terrane accretion and arc magmatism from ~2 Ga to ~ 1 Ga. Here I present a robust construction of Nuna's core cratons (Siberia, Laurentia, Baltica, North China, and Australia). The construction embraces eight major linear tectonic belts with unique geologic piercing points and correlative breakup unconformities across conjugate margins, implying a simple systematic tectonic growth of the supercontinent (Fig. 1). The assembly is not permitted by a dipole, but corresponds to a quadrupole at 1452 +/- 30 Ma, when high quality paleomagnetic data is available for each craton (cf. PALEOMAGIA Precambrian database). In Figure 2, site-mean ChRM declinations and inclinations are plotted at their geographic positions on their respective cratons.

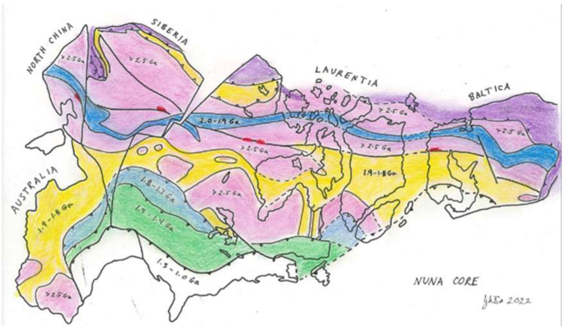

Figure 1. Geological construction of Nuna core.

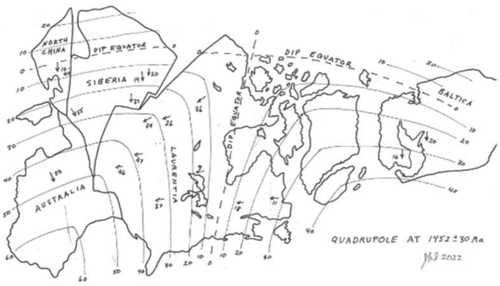

Figure 2. Quadrupole at 1452+/-30 Ma.

Outcrop Observations of Thrust Fault Linkage in a Multilayer with Abrupt Rheological Changes

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In conventional models of thrust fault formation, thrusts form along a base detachment and then propagate upwards through strata, producing a hang-wall anticline. This ‘conventional’ thrust fault geometry commonly fails to match actual outcrop structures. In this study we focus on detailed mapping of a thrust fault outcrop in multilayer strata to investigate the structural evolution and linkage of the fault system.

At Sassoscritto on the Calafuria coast just south of Livorno, Italy an outcrop 10m x 50m exposes a multilayer stratigraphy of sandstones and siltstones that form a thrust stack verging to the SW. The strata provide an ideal test of thrust fault linkage behaviour in a multilayer with abrupt rheological changes; thin bedded units of siltstone-fine-sandstone are encased by thick bedded competent sandstones. Detailed mapping and observations have been made using watercolour sketches and digital photogrammetry to investigate the evolution of the thrust fault system with respect to the strata.

Here we show that across the outcrop, layer parallel thrusts are prevalent except for within a distinct siltstone-sandstone package where a stacked imbricate thrust system is confined. The layer parallel thrust planes are defined by fibrous calcite beef veins between 0.5-5cm thick. There is evidence of sedimentological controls on thrust fault growth and deformation as imbricate systems are confined in silt-sandstone layers bound by coarse sandstones. We interpret these thrust fault geometries to be controlled by variations in multi-layer rheology resulting from heterogeneities in sediment deposition.

The results from this outcrop show that the observed thrust fault geometry does not match conventional models. This work contributes to a series of studies on fold-thrust outcrops to expand the range of conventional models and avoid bias in interpretation of fold-thrust belts.

New insights into a Permo-Triassic rift system: A case study from the Utsira High Area, Northern North Sea

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Due to the multiphase rift development and tectonostratigraphic architecture, the Northern North Sea is an exceptional case study for continental rift dynamic. Shear zone reactivation, discontinuous tectonics and halokinesis have widely influenced fault dynamics and their geometries in the area. Located in the vicinity of the North Sea Triple Junction, the Utsira High and nearby basins are in a key position to understand the evolution of the rift system and the impact those preexisting fabrics had on it. Despite this, the real extent of the Permo-Triassic rift system is still poorly constrained.

Previous work on the Triassic of the area has either focussed on large-scale hypothetical models or on small-scale high-resolution analysis. This study aims to bridge this scale gap linking the structural and sedimentological evolution of the Triassic succession in the study area. Contrast between the different tectonic settings active in the area (from pure rift-related tectonics in the North to salt-related tectonics in the South) and the consequent drainage adjustment is important to include when considering the Triassic evolution of the Utsira High area.

The project uses seismic data and targeted wells to define the tectonic context, create original maps and to provide a new insight into the overall Triassic stratigraphic evolution of the area. Outcomes from this study will represent a step forward in understanding of the evolution of the North Sea Rift System during Triassic time, providing important tools for future exploration, reservoir quality analysis and carbon dioxide sequestration.

The role and control of impurities in the deformation of salt (Ocnele Mari salt mine, Romania)

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Understanding the mechanical behaviour of impure halite dominated salt is important to predict long-term evolution of underground storage caverns and nuclear waste repositories. We have combined fieldwork and photogrammetry with microtectonics and numerical modelling to gain insights into the control that impurity content and distribution has on the long-term properties of rock salt.

The Ocnele Mari salt mine is interpreted as a thrust diapir, it is located in the Romanian Southern Carpathians and provides excellent exposures of layered rock salt which is composed of over 90% halite. The salt here is exploited through both mechanical excavation and solution mining and has also been considered as an option for hydrogen storage.

Layers with different impurity contents (mm to m thick) and some shaly/sandy layers (mm to cm thick) lead to the formation of multiwavelength folds. Fold geometry analysis, combined with numerical modelling provides an estimate for viscosity ratios between the selected layers that can reach up to 20-30. This shows that even small amounts of impurities in rock salt can lead to significant mechanical anisotropy.

Tektonika

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Strain localisation is not primarily controlled by melt fraction in the migmatitic middle crust

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Current prevailing models predict a feedback relationship between deformation localisation and melt fraction, so that deformation zones focuses in areas of higher melt fraction, with further melt migrating into active deformation zones from adjacent volumes. In these models, melt fraction controls where and how strain partitions, i.e. the higher the melt fraction, the weaker the bulk rheology. Whilst this seems to be the case with very low melt fractions, much of the migmatitic middle/lower crust where melt fractions are high shows much more complex behaviour.

In this poster, I will show examples at various scales where deformation and rheology of partially molten bodies is not controlled solely by melt fraction. Particularly at higher melt fractions (over c. 15%) the amount of melt seems to be of secondary importance to other factors in terms of how the body deforms: fabric organisation and fabric heterogeneity, melt crystallisation rate, grain size, or strain rate are equally, if not more, important in controlling deformation style and strain partitioning. I will focus on crustal-scale considerations of melt fraction versus strain rate: the observations imply that crustal melts with high melt fraction, particularly anatectic granite bodies, may ultimately strengthen, not weaken, the crust during orogenic compression. This has profound implications to modelling of the orogenic lithosphere and how lithospheric-scale strain partitions during orogenic compression.

Torvela and Kurhila, 2020, Prec. Res.
Lee et al., 2020, GSL
Butler and Torvela, 2018, JSG
Lee et al. 2018, JSG

Evidence for a time-dependent decrease in fault strength

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Two Mw 6 normal-faulting earthquakes in 2011 and 2016 ruptured the same area of the Mochiyama Fault in mainland Japan just six years apart. By combining geodetic observations of crustal deformation with numerical models of stress transfer, we demonstrate that the Mochiyama Fault could only have been reloaded by up to 50–80% of the 2011 earthquake stress drop between 2011 and 2016. Therefore, the Mochiyama Fault became weaker in the intervening 6 years, with at least a 1–5 MPa drop in the shear stresses needed to break the fault in moderate-magnitude earthquakes. The mechanism(s) that led to this weakening are unclear, but were associated with extensive aftershock seismicity that released a cumulative seismic moment similar to the 2011 main shock. We argue that temporal changes in fault strength do play a role in modulating the timing of moderate-magnitude earthquakes, but may be difficult to detect using geodetic observations alone.

The use of Electron Backscatter Diffraction in Structural Geology

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Electron Backscatter Diffraction (EBSD) provides maps of crystal orientation. I discuss three applications which could assist in a range of structural geology studies.

Deformation by dislocation creep commonly gives rise to crystallographic preferred orientations (CPOs) from which slip systems and hence deformation conditions are deduced. A complementary approach is to look at the lattice distortions within individual grains which give more direct information on slip systems. I will show how the Weighted Burgers Vector method enables this analysis (Wheeler et al. J. Mic. 2009 233: 482; Gardner et al. 2021 396-397).

Misorientation (orientation differences between points) can be used to analyse microstructural processes within grains and at boundaries. I describe an eclogite facies rock from the Alps with an omphacite CPO and a later lower pressure mineral, barroisite, also with a CPO. Interphase misorientation analysis shows that the omphacite affected nucleation of barroisite. The barroisite CPO is a result of this: it is inherited from the omphacite CPO and not formed in a later deformation event (Mcnamara et al. JSG 2012 44: 167).

Dating structural events in deformed rocks is tricky. We need to understand how the parent and daughter isotopes may be affected by deformation. Intracrystalline distortion can provide relatively fast diffusion pathways for parent and/or daughter isotopes. I give an example from the Lewisian Complex where deformed zircon has lost daughter Pb in places and yields younger ages as a result (MacDonald et al. 2013 166: 21).

Collecting EBSD data without hypotheses to test is not advisable, yet it commonly leads to unexpected discoveries relevant for structural geology.