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Virtual AGM 2021
Tectonic Studies Group

5/01/21 - 8/01/21

Abstract Volume

- **Tuesday:** Anglesey Virtual Field Trip – 50th Anniversary Celebration
Iain Stewart Keynote – Open Lecture
- **Wednesday:** Fault Zones and Fault Growth – Fractures and Fluids – Rift Basins
- **Thursday:** Patience Cowie Remembrance Session – Active Tectonics
- **Friday:** Annual Group Meeting – Strain & Microstructures – Orogenesis – Geo-Resources and CO_2 Storage

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BP

**School of Geography, Geology and Environment,
University of Leicester**

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TSG 2021 Virtual Field Trip:

Rhoscolyn, NW Wales

Tuesday 5th January, 9.00 - 12.00

This year, for obvious reasons, the TSG AGM field trip will be different: a *virtual* field trip to Rhoscolyn, Anglesey, NW Wales

The field trip exploits a virtual geological landscape built in a 'game engine' environment, with critical localities added via 3D photogrammetry for enhanced resolution.

The trip will be presented on-line via Zoom, although individual access is also possible, with all files and instructions available for personal download ahead of the field trip.

The trip will be led by Geoff Lloyd (Leeds), with technical assistance from the Leeds Virtual Landscapes team (Ben Craven, Clare Gordon, Jacqui Houghton and Dan Morgan).

The principal aim of the trip is to observe and discuss classic examples of outcrop-scale structures developed in low-grade metasedimentary lithologies and their relevance for understanding the evolution of the regional scale Rhoscolyn Anticline.

In addition, it provides an opportunity to discuss the role of virtual geology in both research and teaching, using this classic location for student field trips as a basis.

The Role of Geology in a Changing World

Join the Tectonic Studies Group and Iain Stewart, Professor of Geoscience Communication (University of Plymouth) and UNESCO Chair of Geoscience and Society, as he discusses the importance of structural geology to meet many of our 21st century challenges - Net Zero, Energy Transition, Natural Hazards and more.

Iain's talk is followed by a panel discussion with structural geologists whose expertise spans: geothermal energy, carbon capture and storage, mining, nuclear waste disposal, hydrocarbons and earthquake hazards.

Panelists:
Tom Blenkinsop, Cardiff University; Zoe Shipton, Strathclyde University; Jonathan Turner, Radioactive Waste Management, David McNamara, University of Liverpool; Zoe Mildon, University of Plymouth.

FREE EVENT
Sign-up on eventbrite.co.uk
#tsg

January 5th 19.30 GMT, 2021

Tues		
9.00-12.00	Geoff Lloyd & Ben Craven	Angelsey Field Trip
12:45	Ken McCaffrey TSG chair	Welcome
12.50	Clare Bond	TSG@50 Introduction
13:00	Rob Butler, with input from Sue Treagus	Themes throughout the years
13:30	Ernie Rutter, Amy Hughes, Betty Mariani	Strain and rock mechanics
14:00	Amicia Lee, John Wheeler, Catherine Mottram, Andrew Parsons	Microstructure, metamorphics and fluids
14:30	Dave McCarthy, Mark Allen, Lucia Perez diaz	Tectonics
15:00	Coffee	
15:30	Mark Cooper, Sian Evans, Frank Peel	Industry, salt, inversion
16:00	John Walsh, Bob Bamburg, Laura Gregory, Lucy Campbell	Faults and Earthquakes
15:30	Jen Roberts, David McNamara, Chris Yeomans	Structural geology and NetZero
17:00	Drinks	
19.30	**Iain Stewart and Panel**	**The Role of Geology in a Changing World - Public Event**

	Presenter *Student	Talk title
Wednesday		
13:00	**Session 1: Fault zones and fault growth**	
13:00	Megan Withers	Using analogue modelling to investigate the development of the Marlborough Fault System, New Zealand
13:15	Jenni Robertson*	Distributed faulting in the tip zone of a crustal-scale normal fault: slip rates since the Late Quaternary point to fault interaction
13:30	Jack Williams	How do faults grow in continental rifts in anisotropic dry crust? Field and microstructural observations from faults in southern Malawi
13:45	Jesús Munoz*	Blueschist-facies paleo-earthquakes in a serpentinite channel enlighten seismogenesis in Mariana-type subduction margins
14:00	**Session 2: Fractures and fluids**	
14:00	Kit Hardman*	The geology and evolution of crystalline basement-hosted, near-surface fissure systems , Calabria, southern Italy
14:15	Luigi Massaro*	New granular rock analogue material for simulation of multi-scale fault and fracture processes
14:30	Flora Menezes	Experimental study on the evolution of shear bands and cracks through multi-stage tests combined with permeability tests
14:45	Tom Blenkinsop	Stress Ratio, Differential Stress, Pore Fluid Pressure and Shear Failure
15:00	Coffee	
15:30	Posters: Faults, fractures, rifts	
16:30	Session 3: Rift basins	
16:30	Torsten Hansen*	Thick- and thin-skinned inversion structures in the Danish Central Graben – the role of multiple salt detachments
16:45	Anindita Samsu	What we talk about when we talk about structural inheritance
17:00	Tim Craig	Short-lengthscale variations in the seismogenic thickness and crustal rheology of East Africa
17:15	Frank Zwaan	Multiphase rotational rifting observed along the Western Afar Margin
17:30	Close	
Thursday		
13:00	**Start and introduction - Session 4: In remembrance of Patience Cowie**	
13:10	Chris Scholz	Patience Cowie and the Inception of Modern Fault Mechanics, A Recollection
13:30	Zoe Shipton	Stress matters! And space and time. And coffee.
13:50	Jon Bull	Fault activity histories of individual faults on timescales of thousands to millions of years
14:10	Luke Wedmore	Controls on the spatio-temporal evolution of strain in early-stage continental rifts in thick lithosphere
14:30	Anneleen Geurts*	The interaction between active normal faulting and landscape evolution in the central Italian Apennines
14:50	Discussion/memories - can run into coffee	
15:00	Coffee break	
15:30	Posters: Active Tectonics	
16:30	**Session 5: Active tectonics talks**	
16:30	Jorien van der Wal*	Active tectonics in slowly deforming, intraplate southern Mongolia
16:45	Gareth L Hurman*	Quantitative analysis of faulting in the Danakil Depression of Afar: the importance of faulting in the final stages of magma-rich rifting.
17:00	Claudia Sgambato*	Influence of fault and shear zone geometry on the stress loading history of active faults
17:15	Robert Churchill*	Exploring Variability in a Global Compilation of Aseismic Afterslip Estimates
17:30	END	

Friday		
11:00-12:00	AGM	
13:00	**Session 6: Strain/microstructures**	
13:00	Xun Xi	Modelling rock fracture induced by hydraulic pulses
13:15	Cat Greenfield	The cumulative effects of pore fabric parameters on rock strength, elastic moduli and sites of fracture initiation
13:30	Sandra Piazolo	Zircon deformation features reveal the shocking nature of deep seismic faulting
13:45	Lucy Lu	Flow strength of wet quartzite in steady-state dislocation creep regimes
14:00	AmiciaLee	Creeping gabbro: dissolution-precipitation creep facilitates deformation in mafic rocks
14:15	Lauren Kedar*	Disorder carbon as a potential strain indicator: a case study in the Haut Giffre, French Alps.
14:30	**Session 7: Orogenesis 1**	
14:30	Jamie Price*	Early deformation in Archaean greenstone belts: layer-parallel shortening versus diapirism in the western Yilgarn Craton, WA
14:45	Phoebe Sleath*	Tectonic Evolution of the Prøven Igneous Complex within the Rinkian Fold-Thrust Belt, West Greenland: Investigation using 3D Photogrammetry
15:00	Coffee and prizes	
15:30	Posters: Strain, orogensesis, reservoirs	
16:30	**Session 7: Orogenesis 2**	
16:30	Eivind Straume*	Global Cenozoic Paleobathymetry with a focus on the Northern Hemisphere Oceanic Gateways
16:45	Alex Tye*	Formation of the Salar de Antofalla depression, Puna plateau, Argentina, by transient extension: an effect of lithospheric foundering
17:00	**Session 8: Geo-Resources and CO2 Storage**	
17:00	Johnathon Osmond*	Potential top and lateral seals for supplemental CO2 storage in Dunlin Group sandstones of the Tusse fault block, northern North Sea
17:15	Paolo Pace	Fracture network modelling in a carbonate reservoir of an old oil field: re-development or moving towards energy transition?
17:30	Close and final awards	

	Presenter *Student	Poster title
Wednesday		
15:30	**Session 1: Fault zones and fault growth (10 posters)**	
Session 1 A	B.M. Behera*	Strength evolution in fault rocks before and after seismic melting from Gangavalli fault zone, Southern India
	D. Muñoz-López*	Episodic evolution of a carbonate thrust zone in the Southern Pyrenees
	S. Masoch*	Structural evolution of a large-scale seismogenic fault in a magmatic arc: The Bolfin Fault Zone (Atacama Fault System)
	Manuele Curzi*	Unravelling brittle faulting in time and space combining structural and X-ray diffraction analysis with K-Ar dating of synkinematic clay minerals. Examples from the central Apennines
	Sam Wimpenny	Weak, Seismogenic Faults in the Lower Crust
Session 1B	J-B P Koehl	Formation of a transform-parallel oceanic core complex along an inherited Timanian thrust, and impact on gas seepage in the Fram Strait
	A Alghuraybi*	The origin of long, unsegmented, underdisplaced normal faults in the SW Barents Sea
	Francesco Iezzi	Throw-rate variations within linkage zones during the growth of normal faults: Case studies from the Western Volcanic Zone, Iceland
	Bailey Lathrop*	Challenging displacement/length scaling laws and the use of global databases to understand the growth of normal faults
	E Delogkos	Fault-bend folding in extensional settings: throw variations and strain partitioning
15:30	**Session 2: Fractures and fluids (10 posters)**	
Session 2A	Angus Odling*	Stress-transfer modelling of dual-stage gold emplacement at the Obuasi deposit, Ghana
	Giampaolo Proietti*	A DFN approach to understand the behaviour of fluid flow in fractured rocks
	Florian Fusseis	The potential role of stylolites in gold mobilization and deposition
	James Shaw*	Structural Controls on the Cavanacaw Gold Vein Deposit, Northern Ireland: Late-Scandian Deformation in the Grampian Terrane of Ulster and Implications for Metallogeny in the Laurentian Caledonides
Session 2B	Hardy Nkodia*	Paleostress reconstruction of brittle deformation in the forland part of the West Congo Belt, Republic of Congo and Republic Democratic of Congo
	Leonardo Del Sole*	Characterization of sub-seismic resolution structural and diagenetic heterogeneities in porous sandstones
	Tom Alcock	Multiscale fracture density analysis at Stromboli Volcano, Italy: implications to flank stability
	Maciej Kani*	Lineament network in the flysh mountain belts: the Gorce Mts. case study
	Richard Jones	Precision and Accuracy of Digital and Analogue Compass-Clinometers
15:30	**Session 3: Rift basins (8 posters)**	
Session 3A	Rich Walker	Hot tip: On the relationship between sheet intrusion tip-shape and stress
	Jonas Koepping*	Emplacement and propagation mechanisms of magma fingers
	Afiq Ali*	Lower crustal buoyancy and viscosity controls on deformation localization during crustal extension
	Tom Phillips	The influence of laterally varying crustal strength on rift physiography – Insights from 3D numerical models
Session 3B	Hamed Fazlikhani	Late to post-orogenic structural configuration in the westernmost Bohemian Massif and SE Germany
	Sarawute Chantraprasert	Interplay between gravity-driven and strike-slip deformation in Upper Neogene sediments, Gulf of Moattama, offshore Myanmar
	William Rutter*	A review of geological and geophysical evidence for major inverted faults at shallow depth beneath the Vale of Glamorgan coast, South Wales, UK
	Frank Zwaan	Analogue modelling of rift segment interaction in orthogonal and rotational extension: implications for the East African Rift
Thursday		
15:30	**Session 5: Active tectonics (12 posters)**	
Session 5A	Paolo Boncio	Applying Tectonics&StructuralGeology to fault displacement hazard analysis: examples from reverse earthquake ruptures
	Luca del Rio*	Active faulting and deep-seated gravitational slope deformation in carbonate rocks (Central Apennines, Italy)
	Mehmet Köküm*	Earthquake Induced Landslides and Liquefaction: 24 January 2020 Sivrice (Elazığ) Earthquake, East Turkey
	Marco Meschis	Regional deformation and offshore crustal local faulting as combined processes to explain uplift through time constrained by investigating differentially uplifted Late Quaternary palaeoshorelines: the foreland Hyblean
	Farha Zaman*	Evidences of Active Tectonics in Nazira-Naginimora area in the Frontal Part of Naga Thrust, North-East India
	Joanna Faure-Walker	Presenting geological data for seismic hazard assessment input
Session 5B	Krzysztof Gaidzik	Seismogenic potential of crustal faults in Central Andes in the light of seismo-lineament analysis
	Jacek Szczygiel	Paleoseismicity of the NE Bohemian Massif: insights from Th-U dating of damaged speleothems and collapsed karst chambers (Niedźwiedzia Cave, Poland)
	John Pappachen*	GPS measured deformation and associated surface strain patterns in the Garhwal – Kumaun region in the Northwest Himalaya
	Ian Pierce	Characteristics of Surface Rupturing Earthquakes in the Walker Lane, USA from Centimeter Scale Imagery & Paleoseismic Trenching
	Marguerite Mathey*	Present-day geodynamics of the Western Alps: new insights from earthquake mechanisms
	Yu Jiang*	Towards understanding the nucleation of earthquakes: Partition of seismic and aseismic slip during a shallow crust earthquake swarm
Friday		
15:30	**Session 6: Strain/microstructures (15 posters)**	
Session 6A	Lucille Carbillet*	Cooking synthetic rocks in the laboratory: preparing “sandstones” with known microstructural attributes
	Auriol Rae	Dynamic Compressive Strength and Fragmentation in Rocks
	Piotr Strzelecki*	Decoding deformed sandstones: an assessment of rock microstructure using X-ray microtomography, image analysis and multivariate statistics
	Vladamir Kusbach	AMS as a tool for interpretation of shear zones: analogue modelling
	Zuzana Roxerová	Deformation localization reflected by the anisotropy of magnetic susceptibility: natural shear zone in calcite
Session 6B	Isabel Ashman*	Dilation and compaction accompanying changes in slip-velocity in clay-bearing fault gouges
	Rebecca Robertson*	Fluid chemistry and earthquake rupture - Investigation of co-seismic chemical reactions: an experimental approach

	Chris Tulley*	Strain and strain-rate dependent rheology of antigorite at mantle wedge conditions – geological evidence.
	Harry Tulley*	The frictional-viscous transition in calcite: how grain-scale heterogeneities control natural deformation
	Liene Spruženiece	The role of the fracture surface in the formation of vein microstructures
Session 6C	Craig Allsop*	A previously undescribed type of synkinematic porosity forming in the strain shadows of rotating porphyroclasts in ultramylonites
	Anna Bidgood	EBSD-based criteria for the identification of the former presence of coesite: application to a metagranite from the Tso Morari dome, Himalaya
	John Wheeler	Analysing crystal distortions to deduce dislocation slip systems
	Chirantan Parui	A comparison of different methods for estimating penetrative strain using natural and synthetic data: A study from the Sikkim Himalaya
	Ben Williams*	Foliation Boudinage Structures at the Mount Isa Cu-Pb-Zn System
15:30	**Session 7: Orogenesis 1 (14 posters)**	
Session 7A	Roger Bissaya*	Dynamics and rheologies of finite deformation in Yaounde and its environs (Cameroon) meta-volcano-sediments, Neoproterozoic and Post-Neoproterozoic
	Fernando Xerxes Gomes	A thermomechanical modeling for the Sergipano fold belt: comparative analysis
	Tim Armitage*	Complex kinematics in a major ductile shear zone, NW Shetland: Evidence of ductile extrusion during Caledonian transpression?
	Caio Pereira	Near Orthogonal Interference Fold Patterns and Geotectonic Meaning of Icaiçara Terrane as part of Accrettion Tectonics in Brazilian-Pan-African Orogeny in Western Gondwana
	Annabel Causer*	Cenozoic relative movements of Greenland and North America by closure of the North Atlantic – Arctic plate circuit
Session 7B	Katharine Groves*	Incision migration across Eastern Tibet controlled by monsoonal climate, not tectonics
	Mark Allen	East Asian orogenic collapse caused by oblique subduction and reduced boundary force
	R.A. Prasath	Possible tearing and faulting mechanism in the lower crust of the Indian Plate: Insights from the Moment tensor inversions of the earthquakes from Garhwal Himalaya.
	Kryzsztof Gaidzik	Structural style of the frontal fold-and-thrust belt and syntectonic mineral vein evolution at the Chachas area in the Western Cordillera (Central Peruvian Andes)
	Dave McCarthy	A re-evaluation of the Variscan Front in Southern Ireland
	Ramy Abdallah*	Quantifying and illustrating uncertainty on interpreted subsurface cross-sections: How to visualise uncertainty by zones and levels?
Session 7C	Tom Jones*	Ductile strain and granite magmatism in the mid-crust of the Damara Orogen, Namibia
	Victor Alania	Two orogens convergence and collision zone: A case study from the Central Caucasus, Georgia
	Enrico Tavernelli	Deformation history of a foredeep basin during its incorporation within an advancing orogenic wedge: the case of the Oligocene-Early Miocene Macigno Costiero Formation, southern Tuscany, northern Apennines, Ita
15:30	**Session 8: Geo-Resources and CO2 Storage (6 posters)**	
Session 8A	Billy Andrews	The role of faults and post-extraction collapse on mine geothermal resevoirs.
	Katherine Ford*	A Multi-proxy Approach for Fracture Network Quantification of Regional Fold and Thrust Structures for Geothermal Reservoir Characterisation
	Rowan Vernon	Surface and subsurface fault mapping of the Flamborough Head Fault Zone to inform groundwater resource management
	Paul Wilson	Stochastic Allan Diagrams for Juxtaposition Analysis

Using analogue modelling to investigate the development of the Marlborough Fault System, New Zealand

M. Withers[1], A. Cruden[1]
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The strike-slip Marlborough Fault System (MFS), located in northeast South Island, New Zealand, has developed to accommodate strain across a plate boundary transition zone between the continental transform Alpine Fault and the congested Hikurangi subduction zone. These four, equally spaced, dextral strike slip faults have the highest earthquake hazard risk in New Zealand and the 2016 Mw 7.8 Kaikoura earthquake, the most structurally complex earthquake recorded in modern history, is associated with the ongoing development of this fault system. Understanding the development of the MFS is critical to understanding how strain is accommodated across the transition zone, and so could provide a framework for earthquake hazard mapping and risk mitigation in northeast South Island.

It is challenging to understand the complex geometries that form in strike-slip systems by analysing finite strain in simple horizontal and vertical sections observed in the field, and there are numerous hypotheses for the development of the MFS based on paleomagnetic and bedding data. In this study, we recreate the tectonic boundary conditions of South Island in scaled analogue models, in order to test the development and evolution of structures through time. The incremental and finite strain is quantified using Particle Imaging Velocimetry (PIV), and X-Ray Computed Tomography (CT) scanning is used to view the internal 3D evolution of the fault system in the model. Results from our experiments show that the MFS has developed sequentially southward as crustal scale Riedel shears to accommodate increasing strain distributed between the Alpine Fault and Hikurangi subduction zone. Our results show how each Riedel shear develops from a zone of diffuse deformation that localises into a single, continuous fault. We discuss how our model differs with existing hypotheses of development of the MFS, and show that our model is consistent with the fault map of the present day transition zone.

Distributed faulting in the tip zone of a crustal-scale normal fault: slip rates since the Late Quaternary point to fault interaction.

J. Robertson[1], G.P Roberts[1], F. Iezzi[1], M. Meschis[1], D. M. Gheorghiu[2], D. Sahy[3], C. Bristow[4], C. Sgambato[1]

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Understanding the deformation that occurs in the tip zones of normal faults is important because (a) it contributes to knowledge on fault growth and linkage, (b) has the potential to inform fault-based seismic hazard analysis about fault connectivity and maximum rupture extent, and (c) influences our understanding of fluid connectivity or otherwise of faulted hydrocarbon reservoirs.

Previous studies into tip zones have demonstrated that displacement gradients vary depending on whether faults are isolated or interacting, particularly that steeper displacements occur close to fault tips where adjacent faults are in close proximity. However, it is not known how these steep displacements develop through time and whether displacement is always localised on a single fault or distributed across fault strands. To address these questions, this study provides measurements of deformation rates across all faults within a tip zone in order to recognise how many individual faults were active simultaneously.

The geometry, rates and kinematics of active faulting in the region close to the tip of a major crustal-scale normal fault in the Gulf of Corinth, Greece, are investigated using detailed fault mapping and new absolute dating. Fault offsets have been dated using a combination of $^{234}U/^{230}Th$ coral dates and in situ ^{36}Cl cosmogenic exposure ages for sediments and wave-cut platforms deformed by the faults. Our results show that deformation in the tip zone is distributed across as many as eight faults arranged within ~700 m across strike, each of which deforms deposits and landforms associated with the 125 ka marine terrace of Marine Isotope Stage 5e. Summed throw-rates across strike achieve values as high as 0.3–1.6 mm/yr, values that are comparable to those at the centre of the crustal-scale fault (2–3 mm/yr from Holocene palaeoseismology and 3–4 mm/yr from GPS geodesy). The relatively high deformation rate and distributed deformation in the tip zone are discussed in terms of stress enhancement from rupture of neighbouring crustal-scale faults.

How do faults grow in continental rifts in anisotropic dry crust? Field and microstructural observations from faults in southern Malawi

J. Williams[1,2], M. Carpenter[1], Å. Fagereng[1], L. Wedmore[2], J Biggs[2], H Mdala[3], Z Dulanya[3], F Mphepo[4]

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The structural evolution of faults in anisotropic crust is poorly understood. This is particuarly true in continental rifts, where pre-existing weaknesses are commonly reactivated and both rift-bounding and intrarift faults exhibit a wide range of lengths and displacements. To investigate how pre-existing weaknesses influence fault growth in rifts, we studied the damage zone of five active normal faults in the amagmatic Malawi Rift, where the crust has experienced successive Proterozoic deformation events at amphibolite to granulite facies conditions. The studied faults are 22-130 km long, comprise a mix of rift-bounding and intrarift faults, and either follow pre-existing fabrics, cut-across fabrics, or are hosted in relatively isotropic post-kinematic intrusions. The estimated displacements are 0.5-2 km and 0.06-1 km for rift-bounding and intrarift faults respectively, which we derived from combining footwall escarpment heights with the thicknesses of hanging-wall sediments indicated by groundwater boreholes. We collected samples in transects along streams that incise through these faults' footwalls. We perform qualitative and quantative microstructure and compositional analyses of these samples using a combination of X-ray diffraction and petrological and scanning electron microscopy.

The footwall-damage zones are expressed in the field by incohesive basement rock. The damage zones have a relatively high microscale fracture density (fracture density ~2-4 mm^{-1} vs <2 mm^{-1} in country rock) and are enriched in smectite and, locally, calcite. Overall there is very little composition variation across these faults and microfractures are typically open. We intepret the minor alteration and lack of vein-filled fractures as evidence of only minor fluid-rock interactions along the studied faults, consistent with a dry crust in Malawi. Footwall damage zones are wider across the high-displacement rift-bounding faults (15-45 m) than across the intrarift faults (5-25 m). Where multiple transects were perfomed across the same fault, the damage zone is wider where the fault cross-cuts surface foliations than where it follows it. Nevertheless, regardless of whether the faults in Malawi follow surface foliations, their damage zones are narrow relative to displacement, compared to global datasets. We attribute this relative lack of damage to: (1) limited fracturing during 'constant length' normal fault growth, (2) the exploitation of deep-seated weaknesses during fault growth, and/or (3) negligible interseismic fault zone healing in Malawi's dry crust, which maintains low cohesion surfaces and reduces the need for progressive damage zone widening. Furthermore, we suggest that as a fault accrues displacement, its structural evolution is not uniform along strike, but will vary depending on the properties of the crust it is hosted in.

Blueschist-facies paleo-earthquakes in a serpentinite channel enlighten seismogenesis in Mariana-type subduction margins

J. Muñoz-Montecinos[1,2], S. Angiboust[1] and A. Garcia-Casco[2,3]

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The architecture and pressure-temperature conditions reached by a Cretaceous block-in matrix serpentinite mélange exposed in the Zagros suture resemble those imaged in the active Mariana subduction zone. There, large magnitude-earthquakes (Mw>8) have never been recorded but smaller events – of poorly-constrained physical origin – in the range Mw ~3-6 are widespread. Field and petro-structural constraints led to a first report of blueschist-facies, fault-related rocks that include breccias, foliated cataclasites and ultracataclasites, all observed within a foliated mafic metatuffaceous block embedded in serpentinite schists. Fine-scale petrological characterization of ultrafine-grained, fluidized cataclastic material reveals the presence of newly-formed glaucophane, lawsonite, phengite, albite and pumpellyite, an assemblage inferred (based on thermodynamic modelling) to have crystallized in the lower lawsonite-blueschist facies at ~0.6-1.0 GPa and 230-300 °C. Extensional veins containing similar mineral assemblages are observed crosscutting the aforementioned rocks but are also identified as comminuted fragments in all fault-related lithologies. Crosscutting relationships among the multiple generations of fluidized ultracataclasites and brecciated blueschists suggest that episodic faulting and hydrofracturing were contemporaneous processes at ~20-35 km depth, i.e., at similar conditions as reported for metabasalts expelled by Mariana serpentinite mud volcanoes. Mechanical modelling confirms that the studied fault-related features can only have formed under nearly lithostatic pore fluid pressure conditions, maintaining the system in a critically unstable regime that promoted recurrent seismic faulting, as monitored in the Mariana seismogenic zone. These fluids are likely associated with externally and deeply-generated fluid pulses that may have reached the seismogenic window, imprinting a Ta-Th-Nb-HREEs-enriched trace element signature. We conclude that this new faulted blueschist occurrence highlights the physical nature and the mechanical processes operating within fault zones in a poorly known region of the subduction channel.

The geology and evolution of crystalline basement-hosted, near-surface fissure systems , Calabria, southern Italy

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The geological characteristics and development of fissure-fill networks are a poorly-understood and under-described phenomenon. In this presentation we examine examples of fissures in exhumed crystalline Carboniferous basement in Calabria, S Italy, and describe their origin, petrology, and geological implications. The fissures cut and reactivate deformation fabrics related to deeper tectonic events and immediately underlie and contain infills related to a Pliocene regional erosional unconformity surface. The reactivation history of the inherited fabrics tracks the progressive exhumation of the plutonic basement, from its emplacement in the Late Carboniferous through veining, folding, and rifting to submarine near-surface fissuring in the Mid Miocene. The fissure network hosts sedimentary and fossiliferous material, collapse breccias, and limited mineralization with vuggy cavities and provides otherwise missing information on the style and history of faulting and sedimentation during the Miocene. In addition these fissures are shown to be an important fluid migration pathway within otherwise impermeable crystalline host rock.

Field observations, palaeostress analyses, and fracture topological analyses demonstrate that these networks of filled-fissures are exceptionally well-connected and penetrate down to depths of at least a kilometre into the upper crust. Analysis of collected samples show that these fissure-fills are typically very porous, resulting in a well-connected network of inter-and-intragranular cavities analogous to other basement reservoirs around the world.

New granular rock analogue material for simulation of multi-scale fault and fracture processes

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Brittle deformation occurs at all observable scales, from the crustal scale of fault systems to the small scale of micro-cracks. Non-linear strain-dependent shear and tensile failure processes on different scales control fault growth and related fracture systems. In this study, we present a new Granular Rock-Analogue Material (GRAM) with a scaling suitable for the simulation of fault and fracture processes in analogue experiments. Dynamically scaled experiments allow the direct comparison of geometrical, kinematical and mechanical processes in the model and nature. The geometrical scaling factor defines the model resolution, which depends on the density and cohesive strength ratios of GRAM and natural rocks. Granular materials like dry silica sands are ideal for the simulation of upper crustal deformation processes due to similar non-linear deformation behaviour of granular flow and brittle rock deformation. We compared the geometrical scaling factor of the common analogue materials applied in tectonic models, which identified a gap for fault-fracture models corresponding to the outcrop and structural scale (1 m – 100 m).

The proposed GRAM is composed of silica sand and hemihydrate powder and is suitable to form cohesive samples capable to deform by tensile and shear failure under variable stress conditions. Based on dynamical shear tests, GRAM is characterised by a similar stress-strain curve as dry silica sand, has a cohesive strength ranging from 2.7 to 7.8 MPa and average density of 1.39 g cm^{-3}. The derived geometrical scaling factor is $L^* = L_{model}/L_{nature} = 10^{-x-x}$ (1 cm in model = 7 – 20 m in nature). Furthermore, GRAM samples were tested in strike-slip analogue experiments. Digital Image Correlation (DIC) time-series stereo images of the experiment surface (Fig. 1) illustrates the localisation and growth of fractures in the strike-slip zone with displacement and strain components in different deformation stages. Early results demonstrate the potential of GRAM to simulate fault and fracture processes and their interaction in fault zones and damage zones during different stages of fault evolution in dynamically-scaled analogue experiments.

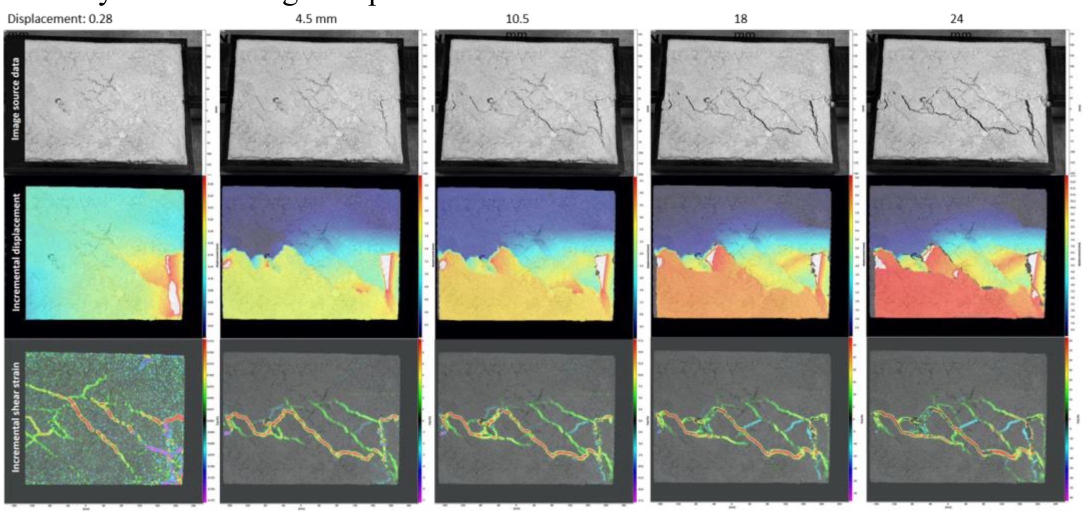

Fig. 1. Time-series images and DIC data of strike-slip zone: a) Image source data; corrected image overlain by b) incremental displacement vector lengths and c) incremental shear strain.

Experimental study on the evolution of shear bands and cracks through multi-stage tests combined with permeability tests

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It is a challenging task to find deformation paths for rocks that have been continuously deformed. How does a rock sample deform if it is already deformed? How much former deformation contains an intact rock sample? Is it possible with aid of laboratory tests to find out an influence of prior deformation or is this behaviour just wildly random? In this work the authors try to explain possible dependencies between mechanical properties and fracture patterns of a Rotliegend sandstone of Permian age (Figure 1). Tests were conducted by increasing confining and pore fluid pressures on fully water-saturated specimens. The investigated Rotliegend sandstone is described in literature as a clearly stratified, poorly permeable rock (3.5 x 10^{-10} m/s) with low porosity values (3 to 8 %). On the basis of multi-step triaxial compression tests and flow tests, shear parameters, volume change, filter velocity and stress-strain-curves of “already damaged samples” are evaluated. Two mainly brittle fracture systems were categorised, which can be distinguished not only by their shape but also by their parameters of friction and cohesion at each loading step. Permeability increased significantly after the first deformation step, however, after following steps, a new increase in permeability is no longer significant. A similar behaviour is observed for stress-strain-curves at most stress states. Specimens in which permeability and strain still increase even after several stress steps are still puzzling.

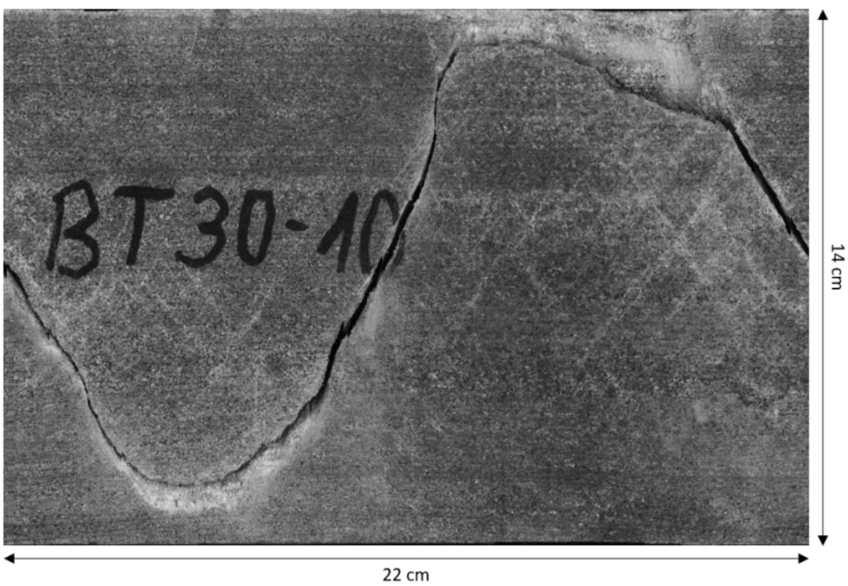

Figure 1. Picture of the lateral surface of a Rotliegend specimen drilled perpendicular to bedding, with 14 cm height and a diameter of 7 cm. The fracture pattern consists of a main shear fracture with subordinates, conjugated pairs of shear cracks. Sample tested with 40 MPa confining pressure and pore pressure from 16 to 32 MPa. Picture taken with a core sample scanner.

Stress Ratio, Differential Stress, Pore Fluid Pressure and Shear Failure

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A composite Griffith-Coulomb failure criterion is commonly applied to explore relations between differential stress and pore fluid pressure, for example on failure mode plots. However this criterion does not account for the intermediate principle stress σ_2. There is increasing experimental evidence that σ_2 does have an important effect on shear failure. Failure criteria that incorporate σ_2 perform better than those, such as the Griffith-Coulomb criterion, that do not.

The extension of the Griffith criterion by Murrell allows the influence of σ_2 to be invesitgated. The stress ratio $\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, pore fluid factor λ, and differential stress $\Delta\sigma$ can all be related through this criterion, accounting for the effect of σ_2 (Fig. 1).

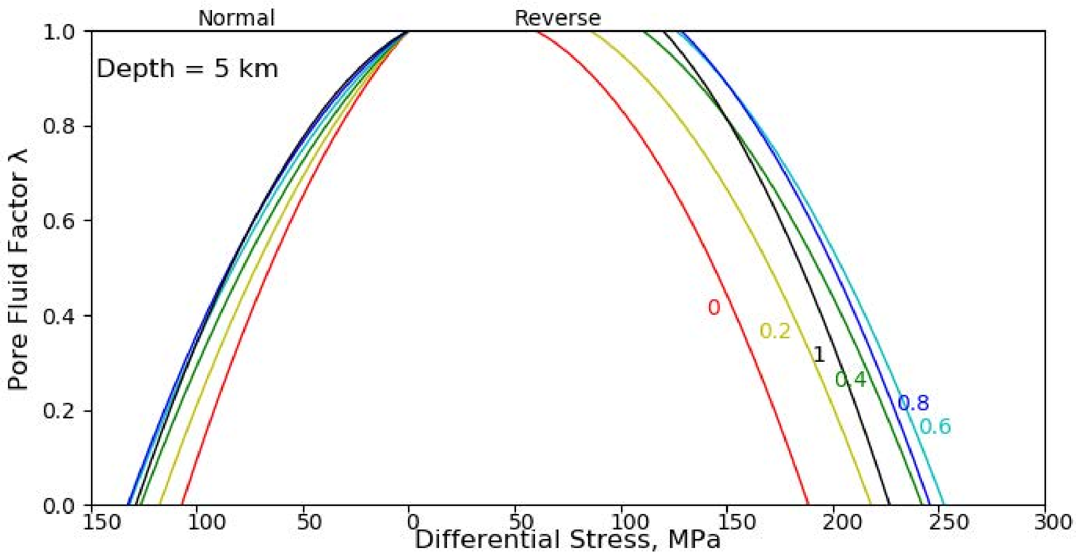

Fig. 1. Pore fluid factor λ vs. Differential stress $\Delta\sigma$ for shear failure using the extended Griffith criterion for different values of stress ratio ϕ shown as numbers on respective curves. Figure calculated for a depth of 5 km.

The stress ratio ϕ has a large effect on the position of the shear failure envelop. The maximum differential stress at most values of pore fluid factor occurs at ϕ~ 0.6; the least value is for ϕ= 0. The value of ϕ is therefore a factor that governs paths to failure in addition to λ_v and $\Delta\sigma$. Cycling between failure and stability may involve changes in all three parameters, which could interact in a dynamic way during failure in the crust. Such considerations may be important where fluids are important for failure, for example in hydrothermal mineralization, and in tectonic environments such as subduction zones.

Thick- and thin-skinned inversion structures in the Danish Central Graben – the role of multiple salt detachments

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From a 3D reflection seismic dataset, we have analysed the kinematic connections of basin-inversion structures to deeper Permian-Triassic salt layers and sub-salt structures in the Danish Central Graben (DCG). The DCG is part of the failed North Sea rift system and, along with many other basins in the region, it experienced post-rift shortening in mainly the Late Cretaceous. Locally, shortening lead to mild basin inversion with relatively limited erosion of former depocentres. Zechstein salt (Upper Permian) is found in varying thicknesses across the study area; mostly it is either absent or only found as a relatively thin layer while the southern part of the area is characterised by several salt stocks and pillows. Where present, it has played a significant role in the structural development, during both extension and subsequent shortening.

A broad zone that experienced significant inversion runs through the study area and strikes approximately NW-SE, mirroring the rift depocentres below. Along its eastern margin, thick-skinned inversion is indicated by open folds formed directly above major rift-bounding basement faults when these were reverse-reactivated. Oppositely, the western margin of significant inversion follows closely the pinch-out of the Zechstein salt. Here, thin-skinned anticlines and monoclines formed above faults soling out into Zechstein salt along inclined halfgraben slopes. Salt rollers and –anticlines underlie the most pronounced inversion structures and seem to have localised deformation during both extension and inversion. Using a triangle-zone concept, antithetic thin-skinned structures can be linked to movements on distant major basement faults via a salt detachment. In the southern part of the study area where thick Zechstein salt occurs, the inverted zone is wider. Within the Triassic carapace, two thin Triassic salt layers form detachments for thin-skinned normal faults along the sloping flanks of major salt structures. Some of these experienced reverse reactivation during shortening, representing the only direct indications of post-rift inversion within the wider inverted zone to the south.

The structural styles we document are similar to those produced by physical-model experiments and to those of other inverted basins in the region. We conclude that especially the Zechstein salt imposed a major control on kinematics during both extension and inversion in the study area. Our thin-skinned tectonic model makes obsolete previous models that incorporated strike-slip movements to explain structures along the western inversion margin. We stress that even relatively even thin salt layers may act as detachments when favorably oriented while elongated salt structures often localise thin-skinned deformation in their overburden. Furthermore, the effects of shortening may be masked by thick salt layers in mildly inverted rifts.

What we talk about when we talk about structural inheritance

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In rift basins, structural inheritance describes the transfer of a structural trait from basement rocks to the overlying sedimentary cover rocks. The local re-orientation of the far-field stress by pre-existing basement structures, whether pervasive or discrete, can influence the geometries, orientations, and connectivity of fractures (including faults) in cover rocks, ultimately impacting the basin's structural architecture. In the literature, the term "structural inheritance" is often used interchangeably with "reactivation", even though there is numerous evidence that inheritance arises from a range of mechanisms. We show this common usage is misleading because different inheritance mechanisms result in – and are reflected in – different geometric and kinematic relationships between basement and cover rocks.

Here we compile knowledge from the existing body of literature and propose a framework for identifying, recognising, and evaluating the potential role of structural inheritance in various rift settings. We summarise the geometric and kinematic relationships between pre-existing basement structures and new fractures in the overlying cover rocks. We also outline the mechanisms of basement-cover interaction and explore inheritance as a process occurring in 3D, discussing its dependency on scale, depth, and accumulated strain. Understanding the various impacts of structural inheritance on the fracture architecture of rift basins can improve characterisation of reservoirs for CO_2 and nuclear waste storage, geothermal energy and mineral exploration, and seismic hazard assessment.

Short-lengthscale variations in the seismogenic thickness and crustal rheology of East Africa

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The well-established variation in the depth of earthquakes along both branches of the East African Rift System offers an opportunity to probe the controls on the depth-extent of seismogenesis, and the length-scales over which this may vary. We present an updated compilation of well-determined earthquake depths from teleseismic and regional seismic data for the East African Rift System, combined with a summary of the depth distribution of smaller-magnitude microseismicity from 13 local network deployments. Large-magnitude earthquakes, unrelated to the movement of magmatic fluids, beneath Afar, the Main Ethiopian Rift, and the northernmost sections of the Eastern Branch, are confined to the upper crust. Seismicity along the Western Branch, and the southern-most sections of the Eastern Branch extends deeper, into the lower crust, in places to depths close to the local Moho. Along the Eastern Branch, in northern Tanzania, the transition between these two regimes occurs over a distance of <40 km, requiring a change to a higher-temperature cutoff for the deeper earthquakes; an effect that must be compositional in origin. Earthquakes deep within the lower crust are therefore likely to be a proxy for an anhydrous composition.

Multiphase rotational rifting observed along the Western Afar Margin

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We focus on the tectonics of the Western Afar Margin (WAM), which is situated between the Ethiopian Plateau and Afar Depression in E. Africa. The WAM is a developing passive margin in a highly volcanic setting, offering unique opportunities for the study of rifting and (magma-rich) continental break-up with regional and global implications.

Earthquake analysis shows that the margin is deforming under a ca. E-W extension regime (a result also obtained by analysis of fault data from recent field campaigns), whereas Afar itself undergoes a more SW-NE extension. Together with GPS data, we see Afar currently opening in a rotational fashion. This opening is however a relatively recent (local) phenomenon, due to the rotation of the Danakil microcontinent modifying the regional stress field (since 11 Ma). Regional tectonics is otherwise dominated by the rotation of Arabia since 25 Ma and should cause SW-NE (oblique) extension along the WAM. This oblique motion is indeed recorded in the large-scale en echelon fault patterns along the margin, which were reactivated in the current E-W extension regime. We thus have good evidence of a multiphase rotational history of the WAM and Afar.

Furthermore, analysis of the margin's structural architecture reveals large-scale flexure towards Afar, likely representing the developing seaward-dipping reflectors typical for magma-rich margins. Detailed fault mapping and earthquake data show that recent faulting is dominantly antithetic (dipping away from Afar), bounding remarkable marginal grabens, although a large but older synthetic escarpment fault system is present as well.

By means of analogue modelling efforts we find that marginal flexure indeed initially develops a large escarpment, whereas the currently active structures only form after significant flexure. Moreover, these models show that marginal grabens do not develop under oblique extension conditions. Instead, the latter model boundary conditions create the large-scale en echelon fault arrangement typical of the WAM. We derive that the recent structures of the margin could have developed only after a shift to local orthogonal extension. These modeling results support the multiphase extension scenario as described above.

Altogether, our findings are highly relevant for our understanding of the structural evolution of (magma-rich) passive margins. Indeed, seismic sections of such margins show very similar structures to those of the WAM. However, the general lack of marginal grabens, can be explained by the common occurrence of oblique extension in nature.

Patience Cowie and the Inception of Modern Fault Mechanics, A Recollection

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Patience Cowie's PhD thesis, conducted with me at Lamont, resulted in three papers, published in 1992, that laid the groundwork for the modern era of fault mechanics studies. In the first paper[1] she reasoned that a cohesive zone model provided a plausible model of fault grown provided that the width of the cohesive zone scales linearly with fault length. In that case, the Griffith instability is avoided and faults grow self-similarly in quasistatic equilibrium. This model is consistent with the existence of faults of all sizes in which displacement scales linearly with length and the fault grows by the breakdown of a damage zone at the fault tip. In the second paper[2] she showed that the then existing data for fault displacement and length were consistent with linear scaling for faults rupturing rock of similar strength. In the third paper[3] she combined the earthquake slip/length scaling law with that fault scaling law to show how faults grow by the accumulation of slip from earthquakes.

In the subsequent thirty years much more work has been done to expand on these themes pioneered by Patience. Here I share some memories of working with Patience in those formative years.

1 Cowie, P. A. & Scholz, C. H. Physical explanation for the displacement-length relationship of faults using a post-yeild fracture mechanics model. *J. Struct. Geol.* **14**, 1133-1148 (1992).

2 Cowie, P. A. & Scholz, C. H. Displacement-length scaling relationship for faults: data synthesis and discussion. *J. Struct. Geol.* **14**, 1149-1156 (1992).

3 Cowie, P. A., and Scholz, C.H. Growth of faults by accumulation of seismic slip. *J. Geophys. Res.* **97(B7)**, 11085-11095 (1992b).

Stress matters! And space and time. And coffee.

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Patience Cowie was a truly outstanding scientist. Her research spanned several disciplines of structural geology and tectonics. She made a lasting contribution to every discipline she published in and as well as academic advances, produced significant impacts in industry and earthquake hazard assessment. Her PhD investigated the tectonics of mid-ocean ridge faulting and investigations of fault mechanics and fault population scaling. Although papers in both topics established her reputation as a world-class scientist at an impressively early stage of her career, it was her research in the second topic that was a genuine game-changer. The implications of this work for predicting fault patterns and linkage have been crucial for the development of models from 3D seismic data, and for examining the interplay between faults, the basins they bound and the sediments they host. More recently she explored relationships between fault geometry, slip rate and recurrence intervals along seismically active faults, with important implications for earthquake hazard assessment.

Patience's drive to constrain physical explanations of the underlying dynamics of Earth processes meant her numerical modelling was always firmly grounded in field observations. Her models incorporated the effects of stress in time and space as fault system evolved, but always underpinned by geometric and kinematic observations in the field. She loved fieldwork and her joy at the beauty of geological structures was infectious and inspiring.

And she made a mean field coffee.

Fault activity histories of individual faults on timescales of thousands to millions of years

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Determination of fault growth rates and fault network evolution at timescales from 10^4 to 10^6 years has been hampered by lack of well-constrained stratigraphic successions that provide high-fidelity records of fault development over these time periods. Here I show how seismic reflection data of different spatial resolutions can be used to constrain the linkage history and displacement rate variations of single faults. Using examples from New Zealand and Greece it is shown that while the length of faults is established rapidly (100s kyr to 1 My), it is possible to determine the linkage and growth of histories of faults. Displacement rate on a linked fault system can be greater than rates on the preceding unlinked system.

Focussing on shorter timescales, the spatial and temporal accumulation of slip from multiple earthquake cycles on active faults is poorly understood. A methodology is described that can determine the time period of observation necessary to reliably constrain fault behaviour, using a high-resolution long-time-scale (c. last 20 kyr) fault displacement dataset. This indicates temporal and spatial variability in incremental displacement associated with surface-rupturing slip events. There is spatial variability in slip rates along fault segments, with minima at locations of fault interaction or where fault linkage has occurred in the past. This evidence suggests that some earthquakes appear to have been confined to specific segments, whereas larger composite ruptures have involved the entire fault. The short-term variability in fault behaviour suggests that fault activity rates inferred from geodetic surveys or surface ruptures from a single earthquake, may not adequately represent the longer-term activity nor reflect its future behaviour. Different magnitude events may occur along the same fault segment, with asperities preventing whole segment rupture for smaller magnitude events.

Controls on the spatio-temporal evolution of strain in early-stage continental rifts in thick lithosphere

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The distribution of strain and the development of faults during the early stages of continental extension affects the style of later-stage rifting and the eventual breakup of the lithosphere. Cowie et al. (2005) showed how coupling between brittle deformation and the evolving structure of the lithosphere in the northern North Sea caused initially widely distributed deformation to become focussed at the rift axis during lithospheric extension in the Late Jurassic. However, in many regions, the evolution of strain through time is obscured by later stage sedimentation or magmatism. Here we integrate observations from high-resolution topography of active faults in the southern Malawi rift to capture the spatio-temporal patterns of strain during early stage continental rifting in thick (>150 km) amagmatic lithosphere.

We focus our observations on two grabens in southern Malawi, the Zomba and Lower Shire graben. In the Zomba Graben, we find evidence for five sub-parallel Late Quaternary faults scarps. The scarps are segmented along strike, have a 10-15 km across-strike spacing and are up to 30 m high. The along-strike scarp height profile on the Chingale Step fault has evidence for multiple earthquake ruptures: the cumulative scarp shows evidence for three segments whereas the most recent rupture appears un-segmented. This suggests that segment linkage has occurred rapidly during the Late Quaternary, and before the fault has accumulated a large amount of displacement (< 1 km total displacement). The scarp height measurements within the Zomba Graben suggest that 54 ± 24 % of strain is currently occuring across the intra-rift faults.

In contrast to the Zomba Graben, the Lower Shire Graben has been active during previous episodes of extension, and the current faults have reactivated Jurassic-Cretaceous and Karoo-age (~360-200 Ma) structures. Along the Thyolo border fault, a 30-m high fault scarp demonstrates activity during the current phase of rifting. The scarp shows evidence for three segments; however, the segment boundaries do not align with changes in the trend of the fault surface trace, which both follow and cross-cut the metamorphic foliation.

We suggest that observations from the Zomba and Lower Shire grabens are best explained by reactivation of viscous mid-crustal structures which in-turn guide deformation in the brittle upper crust. In this interpretation, during early-stage rifting in the dry, thick and cold lithosphere of southern Malawi, mid-crustal heterogeneities play a more important role in localising strain than brittle structures observed at the surface.

The interaction between active normal faulting and landscape evolution in the central Italian Apennines

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Drainage network and basin stratigraphic development in continental rifts is often explained by the growth and structural linkage of fault segments that affect the topography of intra-basin areas and in turn the connectivity of the drainage network. Here we use the central Italian Apennines to demonstrate the contribution of the river network itself to long-term (~3 Myr) drainage network evolution and basin stratigraphy. We integrate stratigraphic, geomorphic and fault slip datasets for one of the largest river systems in the area (the Aterno river system) and compare this compilation with insights from regional-scale numerical modelling work.

This compilation shows that most basins in the central Apennines were initially isolated during the early Pleistocene, but became progressively fluvially integrated with one another during the Middle to Late Pleistocene. We demonstrate that rates of sedimentation and basin subsidence in the central Apennines are well-matched and that only small increases in sediment and water supply relative to basin subsidence are needed to allow basins to overspill and fluvially integrate with adjacent basins. We conclude that at a regional-scale, an increase in sediment and water supply relative to basin subsidence can be explained by the Early to Middle Pleistocene climatic transition, the progressive increase in fault-related topography, and the transport of sediment and water down-system as drainage integration occurred. Slip acceleration associated with fault interaction, on the other hand, can explain re-establishment of isolated conditions in some hanging wall depocentres during the Late Pleistocene.

This data compilation from the central Apennines demonstrates that drainage network evolution in continental rifts is not simply a result of fault evolution but needs to be considered as a factor in its own right. Although fault linkage favours drainage integration, these developments are not necessarily related and occurring simultaneously. In general, this work highlights the importance of drainage network evolution for topographic development, sediment dispersal, and basin stratigraphy in continental rifts, and its potential contribution to feedbacks between surface processes and tectonics and to temporal variations in fault activity over time.

Active tectonics in slowly deforming, intraplate southern Mongolia

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The southern Mongolian landscape is characterised by multiple tectonic terranes that actively deform as a result of far-field stresses related to the India-Eurasia collision. Four major M~8 earthquakes in the 20th century indicate a localisation of strain within the mountain ranges that suround the rigid Hangay Dome in central Mongolia. The Mw~8.1 Gobi Altai earthquake of 1957 created left-lateral, oblique and reverse surface ruptures along >350 km of the Bogd fault that marks the mountain front of multiple restraining bends. Local palaeoseismological research along the fault determined 0.5-1 mm/yr strike-slip and <0.3 mm/yr vertical slip rates, and established that similar earthquakes to the 1957 event have occurred every 3-5 ka. However, it remains unclear whether the kinematics along the Bogd fault are regionally representative, especially in consideration of the heterogeneity of intraplate tectonics. We extrapolate the results from local palaeoseismological studies to a larger spatial and temporal scale to evaluate the effects of active tectonics on landscape evolution within the context of regional climate variations. This allows for improved interpretations of tectonically altered landforms and palaeo-environmental reconstructions, and can contribute to better seismic hazard assessments. Regional and local analysis of digital elevation models, surface exposure and OSL dating, ground-penetrating radar analyses, geological and geomorphological field data, and seismic reflection data show that deformation in southern Mongolia is not limited to the strand of the Bogd fault that ruptured in 1957. Rather, multiple sub-parallel fault strands may be active simultaneously, and numerous faults that have previously not been described are located between the Gobi Altai and the Hangay. These faults in the Valley of Gobi Lakes move at vertical slip rates that are cumulatively comparable to the Bogd fault, and either describe a northward translation of the deformation front or an accommodation structure at the margin of a rigid crustal block. The correlation of faults in seismic reflection data with geomorphological inconsistencies in the Valley of Gobi Lakes implies that the newly mapped faults may be linked to the Bogd fault system. However, their effects on landscape evolution may be masked by erosion and deposition rates that surpass deformation rates in the basin. The structure of the southern Mongolian subsurface remains to be corroborated by further data, however it seems clear that active tectonics has played in important role in the evolution of the southern Mongolian landscape. The broad width across which deformation is distributed highlights the complexity of intraplate tectonics and serves as a reminder to incorporate regional analyses of tectonic geomorphology for more accurate seismic hazard assessments.

Quantitative analysis of faulting in the Danakil Depression of Afar: the importance of faulting in the final stages of magma-rich rifting.

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Despite the importance of magmatism in magma-rich rifts, faulting still accommodates significant amounts of extension. However, the influence of magmatism on fault evolution is poorly constrained, as is the importance of mechanical deformation, during the final stages of magma-rich rifting. The Danakil Depression (Afar, Ethiopia), located between the Ethiopian Plateau and Danakil Block, is undergoing the final stages of continental break-up with extension focused to narrow axial magmatic segments. Therefore, the region provides the ideal natural laboratory to conduct a quantitative, high resolution study of fault activity and interaction in a magma-rich rift setting.

In this study, >600 faults and fractures were mapped along the rift axis of the Danakil Depression using remote sensing, with lengths ranging from <500 m to >10 km. Along the axial magmatic segments, fault scarp offsets are typically <20 m, however increase away from the volcanic centres, reaching >100 m at the northern and sourthern ends of the basin. Fault density also varies along the rift axis with increased densities at magmatic segment tips (>3.8 km/km^2), as well as step-over zones (2.65 km/km^2) between segments. However, the Erta-Ale magmatic segment has the lowest fault concentrations in the study region. Orientation trends along the axis were identified, with faults in the northern and central parts of the basin orientated NNW/SSE. In the south, fault orientations are more variable, including a conjugate set (N/S and NNW/SEE) of structures across the Giulietti Plain. Using the Tuckwell et al. (1996) model, we characterised the mode of extension from the geometrical relationship between fault strike, rift orientation and extension direction. In the northern and central parts of the basin, the relationship between fault strikes and the regional NE/SW extension direction indicates transtensional opening. Oblique opening is occurring in the south of the depression due to localised tectonic forces between magmatic segments. Recent seismic activity in the depression is focused along the rift axis, with earthquake clusters at step-over zones, indicating the axial faulting to be active. In addition, focal mechanisms support the varying modes of opening occurring in the Danakil Depression.

The increase in fault density and offset away from volcanic centres (e.g. Erta-Ale) suggests along basin variations in the contribution from faulting to extension. Faulting charatcterstics, such as orientation, are also influenced by magmatic segments along the rift axis of the Danakil Depression. In addition, faulting is shown to still be crucial in accommodating extension and controlling the architecture of magma-rich rifts in the final stages of continental break-up.

Influence of fault and shear zone geometry on the stress loading history of active faults

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A key question for seismic hazard assessment is what controls the stress-loading to failure in earthquakes, whether the stress-loading appears to be random or to an extent explainable, given constraints on fault interaction and the build-up and release of stress over many earthquake cycles.

We investigated the historical earthquake sequence occurring on the Southern Apennines fault system, where 25 active normal faults are arranged predominantly along strike from each other. This particular aspect of the fault system allowed us to isolate the effects of regional tectonic loading from across- and along-strike fault interaction, because in places only a single fault accomodates all of the regional deformation, whereas elsewhere the tectonic strain is shared by several faults across strike. We conducted an analysis of the Coulomb stress changes due to interseismic loading and 25 earthquakes with Mw > 5.5 occurring over 6 centuries.

Our results show that where only one fault exists across strike, stress loading is dominated by the regional tectonics through slip on underlying shear zones and fault planes have spatially smooth stress with predominantly time-dependent stress increase. Conversely, where several faults are stress-loaded by across-strike fault interactions, fault planes have more irregular stress patterns and stress loading histories are influenced by interaction with nearby faults. Thus, some aspects of the stress-loading to failure in earthquakes appear not be random, since stress-loading is not the same for all faults and is dependent on the geometry of the fault/shear-zone system.

Full article:
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Exploring Variability in a Global Compilation of Aseismic Afterslip Estimates

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Geodetic observation and modelling of aseismic afterslip have led to a body of case studies that show significant variation in first-order characteristics, such as aseismic moment release relative to coseismic moment, and the depth ranges of aseismic slip. A better understanding of these properties and their variability may provide valuable insights into fault-zone behaviour, the earthquake cycle and aftershock triggering.

We compile a database of ~150 studies that model aseismic afterslip in the wake of ~50 Mw6.0+ earthquakes since 1979. We first determine the variability in relative afterslip moment. We then explore how mainshock characteristics (e.g. magnitude, rake, depth, tectonic setting), modelling approach (geodetic analysis, kinematic and dynamic slip modelling), data (e.g. data-type, observation window, potential biases) and modelling parameters (e.g. model domain, co-modelling of other postseismic mechanisms, shear modulus etc.) may systematically favour higher or lower relative afterslip estimates.

We find the first-order control on afterslip moment is coseismic moment (bootstrapped correlation coefficient 0.92±0.01), but that considerable variability exists beyond this. For example, the ratio of afterslip moment to coseismic moment varies from less than 1% to over 300%, with the interquartile range spanning 7 to 33%. Observational limitations (start & end-time) do not appear to explain variation in global estimates of relative afterslip moment. However, different estimates from individual events, such as the 2004 Sumatra megathrust, vary by more than one order of magnitude, and suggest some variation in afterslip moment is an effect of data and modelling. Relative afterslip moment may be related to local strain-rate and plate velocity, which are effectively proxies for the local rheological regime. Furthermore, globally, relative afterslip moment has a weak negative correlation (bootstrapped correlation coefficient -0.21±0.07) with mainshock size. This could be due to a bias whereby studies following smaller events are only published if afterslip is relatively high.

We suggest that variation in relative afterslip moment is related to the local rheological and tectonic setting, but as such variation exists between models for the same event, that modelling differences and methodological choices are barriers to systematic comparisons. We also find aseismic afterslip is prevalent at coseismic rupture depths as well as up- and down-dip of the mainshock rupture, perhaps reflecting the importance of rheological heterogeneity at typically velocity-weakening depths.

MODELLING ROCK FRACTURE INDUCED BY HYDRAULIC PULSES

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Soft cyclic hydraulic fracturing has become an effective technology used in subsurface energy extraction which utilises cyclic hydraulic flow pressure to fracture rock. This new technique induces fatigue of rock to reduce the breakdown pressure and potentially the associated risk of seismicity. To control the fracturing process and achieve desirable fracture networks for enhanced permeability, the rock response under cyclic hydraulic stimulation needs to be understood. However, the mechanism for cyclic stimulation-induced fatigue of rock is rather unclear and to date there is no implementation of fatigue degradation in modelling the rock response under hydraulic cyclic loading. This makes accurate prediction of rock fracture under cyclic hydraulic pressure impossible. This study develops a numerical method to model rock fracture induced by hydraulic pulses with consideration of rock fatigue. The fatigue degradation is based on S-N curves (cyclic stress vs cycles to failure) and implemented into the constitutive relationship for fracture of rock using in-house FORTRAN scripts. The cohesive crack model is used to simulate discrete crack propagation in rock which is coupled with hydraulic flow and pore pressure capability. The developed numerical model is validated via experimental results and then a new loading strategy for pulsating hydraulic fracturing is proposed. It has been found that hydraulic pulses can reduce the breakdown pressure of rock by 10%-18% upon 10-4000 cycles. Using the new loading strategy, a slow and steady rock fracture process is obtained while the crack stress is reduced.

The cumulative effects of pore fabric parameters on rock strength, elastic moduli and sites of fracture initiation

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The strength of porous rocks in the subsurface is critically important across the geosciences, with implications for fluid flow, mineralisation, seismicity, and the deep biosphere. Most studies of porous rock strength consider the scalar quantity of porosity, in which strength shows a broadly inverse relationship with total porosity; pore fabrics are seldom considered. In sedimentary rocks, pore shape is controlled by grain shape, size, and size distribution. Volcanic and igneous rocks can exhibit strongly anisotropic pore shapes and pore fabrics, and pore distributions can be heterogenous and anisotropic, independent of the rock matrix. Here we use finite element models, constructed in COMSOL, to consider poroelastic interactions related to individual and cumulative pore fabric characteristics, such as pore aspect ratio, pore-pore distance, and pore orientation with respect to an applied stress state. We simulate elastic-brittle conditions through rock failure, and implement Mohr-Coulomb damage growth in the host material, to determine the role of pore fabrics in controlling fracture nucleation in variably porous materials.

We find that, relative to isotropic pore space, increased pore aspect ratio (major axis/minor axis) reduces Young's Modulus and increases stress concentrations at the pore wall. Altering pore orientation changes the effective load bearing area, thereby changing the stress concentration, and moves the location of maximum stress on the pore surface. Pore-pore interaction may lead to the maximum stress concentration being shifted from the pore wall into the intervening material; suggesting not all fractures nucleate in tension, nor at the pore wall.

Failure mode, damage growth, and fracture distribution are dependent on pore aspect ratio, orientation, arrangement and proximities. The pore fabric is thus important to the mechanical properties and strength of rocks. The nature and style of resulting damage has important implications for the bulk rock strength, and for the evolving fluid flow properties of initially low-porosity rocks.

Zircon deformation features reveal the shocking nature of deep seismic faulting

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Rocks that have undergone seismic faulting provide invaluable information to constrain faulting mechanisms. Within the Ivrea zone, Italy, deformation features in zircon grains located both within and in the immediate vicinity of pseudotachylyte allow identification of mechanisms involved and their sequence during the earthquake cycle. The dynamic shear fracture associated with seismic faulting causes, at the propagating fracture tip, a damage zone of several centimeters. In the damage zone, high stresses induce generation of very high dislocation densities causing continuous crystal lattice bending throughout whole zircon grains and distinct planar deformation bands. In-situ grain pulverization of crystal-plastically deformed grains is interpreted to be due to the alternating volumetric contraction and expansion of a propagating seismic shear fracture. Micro-twins are present whose formation has been shown to indicate pressures otherwise only known from impacts (~20 GPa). Subsequent physical displacement along the shear fracture surfaces results in pseudotachylytes formation.
Our results suggest that the initiation and propagation of a dynamic shear fracture causes at its tip a damage zone where pressures are heterogeneously in space, magnitude and sign resulting in both ductile and brittle deformation features similar to those observed during impact related shock metamorphism.

Flow strength of wet quartzite in steady-state dislocation creep regimes

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An accurate flow law for dislocation creep of quartzite is critical for the understanding of continental rheology and geodynamic models. Despite many years of effort, existing creep experiments have yielded very different quartz flow law parameters. The significant difference in flow law parameters will translate to large uncertainties in the predicted strength of continental crust and mat have profoundly affected the outcomes of geodynamic models where a quartz flow law is used.

We demonstrate that the discrepancies in quartz flow law parameters among existing studies can be explained by considering both the pressure effect on the activation enthalpy (Lu and Jiang, 2019) and the slip system dependence of the stress exponent (Tokle et al., 2019). From a current dataset of creep experiments of wet quartzite with microstructures and c-axis fabrics suggesting steady-state dislocation creep and building on previous work, we determined flow law parameters corresponding to dislocation creep by dominant prism <a> slip and dislocation creep by dominant basal <a> slip systems. The parameters of two flow laws are determined from experiments through an iterative approach. The flow law for dislocation creep by dominant prism <a> slip is $\dot{\varepsilon} = 9.4\times10^{-16} f_w^{2.6} \exp\left(-\frac{132000+35.8P}{RT}\right)\sigma^4$ and that by dominant basal <a> slip is $\dot{\varepsilon} = 4.2\times10^{-11} f_w^{1.7} \exp\left(-\frac{126000+23.1P}{RT}\right)\sigma^{2.5}$. Quartz c-axis fabrics from both experiments and nature suggest that wet quartzites commonly flow by a continuous combination of prism <a> and basal <a> slips. In such a case, quartzite is a polycrystal aggregate in which the slip system varies among grains. On a suitable representative volume element, the overall rheology of a quartzite must be obtained through a self-consistent micromechanics approach. We propose a numerical method to determine the creep behaviour where both basal <a> and prism <a> slips are significant and plot the overall strength versus temperature and contributions of dominant slip systems in a 3D profile. We also discussed the significance and implications of multiple flow behaviours for continental strength.

Creeping gabbro: dissolution-precipitation creep facilitates deformation in mafic rocks

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Mafic rocks consist of strong minerals (clinopyroxene, plagioclase) that can only be deformed by crystal plastic mechanisms at very high temperatures. Yet, mafic rocks do show extensive deformation by non-brittle mechanisms when they have only reached lower temperatures. In many of such cases, the deformation is accommodated by an interaction of deformation with simultaneous mineral reactions. Here we show that dissolution-precipitation creep plays a major role in deformation of gabbro lenses at upper amphibolite facies conditions.

The Kågen gabbro in the North Norwegian Caledonides intruded the Vaddas Nappe at 439 Ma at pressures of 7-9 kbar, temperatures of 650-900°C (and depths of ~26-34 km). The Kågen gabbro on south Arnøya is comprised of undeformed gabbro lenses with sheared margins wrapping around them. This contribution analyses the evolution of the microstructures and fabric of the low strain gabbro to high strain margins. Microstructural and textural data indicate that preferential crystal growth of amphibole grains in the extension direction has produced the deformation microstructure and the CPO. Dissolution-precipitation creep is inferred to be the dominant deformation mechanism, where dissolution of the gabbro took place in reacting phases of clinopyroxene and plagioclase, and precipitation took place in the form of new minerals: amphibole and garnet. Synchronous deformation and mineral reactions of clinopyroxene suggests mafic rocks can become mechanically weak during the general transformation weakening process, i.e. the interaction of mineral reaction and deformation by diffusion creep. The weakening is directly connected to a transformation process that facilitates diffusion creep deformation of strong minerals at far lower stresses and temperatures than dislocation creep. Initially strong lithologies can become weak, provided that reactions can proceed during deformation, the transformation process itself is an important weakening mechanism in mafic (and other) rocks, facilitating deformation at low differential stresses.

Disorder carbon as a potential strain indicator: a case study in the Haut Giffre, French Alps.

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Crustal rocks commonly contain organic carbon in varying concentrations. When a rock is exposed to increased temperatures or high strain rates, the amorphous nanostructure of fossilised organic matter is altered, breaking down the carbon structure and progressively re-ordering it into graphitic sheets, which carry an inherent weakness. However, in most sedimentary rocks, particularly at low thermal maturities, the carbon ordering process does not progress to full graphitisation. This means that the majority of organic carbon occupies a nanostructure somewhere between the amorphous and graphitic endmembers, and these intermediate structures are less well-understood.

The presence of graphitic carbon on fault planes and in aggregates has been shown to reduce the coefficient of friction during brittle deformation. In ductile regimes, the occurrence of a crystallographic preferred orientation (such as in graphite) is thought to control the localisation of subsequent tectonic events. Although the role of graphitic carbon in strain localisation is recognised, little work has been done to understand whether partially ordered carbon can also weaken the rock.

In this study, we use Raman spectroscopy to assess carbon nanostructure in a suite of variably strained samples, collected from a sequence of thrust-stacked carbonates in the French Alps. We assess strain through a combination of field observations, optical microscopy, and EBSD analysis. By analysing bulk samples through transects of faults and shear zones, we show a distinct shift in certain Raman spectral parameters in zones of high strain. We also map these parameters on a sub-mm scale across the surface of intact rock chips to establish the scale of variation and therefore explain the distribution of data. By comparing this targeted Raman mapping process to optical microscopy and EBSD mapping, we are able to directly compare small-scale variations in carbon nanostructure to strain-related microstructural variations in the rock.

This work highlights the importance of disordered carbon in strained rocks when studying rheological behaviour. Our results suggest that not only is organic carbon mechanically altered on multiple scales, but that it may be possible to separate the strain-related Raman signal from that of temperature, opening up the possibility for the use of Raman as a quantitative strain indicator. We also infer that disordered carbon may influence strain localisation through cycles of rock weakening.

Early deformation in Archaean greenstone belts: layer-parallel shortening versus diapirism in the western Yilgarn Craton, WA

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The mechanisms responsible for early deformation in Archaean greenstone belts have long been contended, owing to the overprinted, deformed and commonly ambiguous nature of early-formed structures. Whereas some researchers document evidence favouring early periods dominated by horizontal tectonics, such as layer-parallel shortening, others favour models entailing vertical tectonic processes such as granitic diapirism. Unlike most parts of the well studied Yilgarn Craton of Western Australia, the Rothsay area in the westernmost part of the craton, has remained unmapped and essentially unstudied. The Rothsay area comprises a ~8 km-thick succession of ca. 2.8 Ga mafic-ultramafic volcanic rocks, banded iron formations and volcaniclastic units, intruded by a suite of mafic-ultramafic layered sills. Rocks in this area have been deformed into a complex 15 km-scale outward-dipping fold structure, dissected by multiple shear zones that host economic lode-gold mineralisation (Fig. 1). To better understand the early deformational history of the Rothsay area, detailed 1:25,000 scale geological mapping has been undertaken.

The earliest structures observed at Rothsay consist of a pervasive layer-parallel (S_1) fabric in weaker units that is consistently oriented parallel to bedding (Fig. 1). In combination with the laterally discontinuous nature of some units (Fig. 1), this could be interpreted as evidence of an early layer-parallel shortening episode, as suggested in other Archaean terranes. However, detailed structural mapping advocates an early phase of granite diapirism (D_1) and associated layer-parallel shearing to account for the (originally) domal architecture of the area and the associated S_1 fabric. The discontinuous nature of some supracrustal units can be fully accounted for by intrusive geometries. Subsequent shortening episodes have resulted in refolding, a regional (S_3) fabric, shearing (D_4) and faulting. This work is compatible with recent regional structural analysis that indicates a crucial role for diapirism in the early structural development of the western Yilgarn Craton.

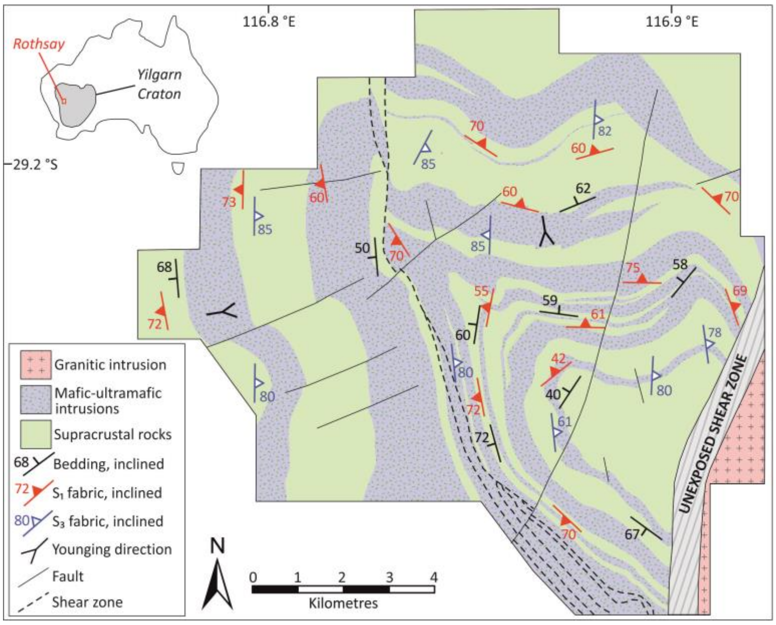

Fig. 1: Geological sketch map of the Rothsay area, showing the geometry of mafic-ultramafic intrusions, bedding, major fabrics, faults and shear zones.

Tectonic Evolution of the Prøven Igneous Complex within the Rinkian Fold-Thrust Belt, West Greenland: Investigation using 3D Photogrammetry

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The amalgamation of cratons and subduction of oceanic lithosphere in the Paleoproterozoic has formed linear orogenic belts worldwide, such as the little studied Rinkian fold-thrust belt on the west coast of Greenland. The Rinkian comprises a Paleoproterozoic shelf sequence formed on the margin of the Rae craton that was deformed by basement-core nappes in a high-grade deformation event at c. 1.82Ga. The northern part of the area affected by the Rinkian fold-thrust belt includes the Prøven Igneous Complex (PIC), a ca. 90 x 80 km large intrusive complex of orthopyroxene-bearing monzogranite to quartz monzonite, which was intruded between ca 1.87-1.9 Ga. The PIC was previously considered to be a syntectonic intrusion, so new work on the structural evolution is important. Here we use detailed photogrammetric mapping on 3D Stereo Blend at the GEUS Photogeological Laboratory in Copenhagen, combined with previous survey work, to identify the major deformation phases of the PIC and their associated structures. We found that the PIC formed as a large sheet intrusion which has been deformed by a westward facing thrust series, developing type II interference fold patterns. This is especially prevalent at the base PIC-metasediment contact, where incompetent rock – partially molten paragneisses and leucogranites – have produced more intense deformation. Furthermore, within the main PIC competent body a type I interference fold pattern has developed between large scale perpendicular folds. Our results demonstrate that the PIC was likely emplaced in situ at shallow crustal levels, and then deformed by the Rinkian orogenic belt. This study has provided new insights into the deformation history of the Prøven Igneous Complex and the tectonic setting for the Rinkian fold-thrust belt overall. Furthermore, the project shows how remote mapping through photogrammetry can cover large areas in revealing detail.

Global Cenozoic Paleobathymetry with a focus on the Northern Hemisphere Oceanic Gateways

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In the Cenozoic time (66-0 Ma), the evolution of oceanic gateways linking the major oceanic basins have facilitated ocean circulation and climate changes. However, the timing of these oceanic gateway events is poorly constrained and is often neglected in global paleobathymetric reconstructions. Therefore, we have developed a new global paleogeography model focusing on the evolution key oceanic gateways. Our model is based on recent compilations of oceanic lithospheric ages and sediment thickness (GlobSed), and incorporates updated regional plate kinematics, and reconstructed oceanic plateaus and microcontinents. We provide detailed models of the Northern Hemisphere oceanic gateways, in particular, the new paleobathymetry model incorporates Northeast Atlantic paleobathymetric variations due to Iceland mantle plume activity. The model documents important bathymetric changes in the Northeast Atlantic and in the Tethys Seaway close to the Eocene – Oligocene transition (~34 Ma). This was the time of the first glaciations of Antarctica, often belived to be triggered by the opening of the Southern Ocean gateways (i.e. the Drake Passage and the Tasman Gateway) and subsequent Antarctic Circumpolar Current initiation. Our reconstructions can be used to test whether the Northern Hemisphere gateways could have played an important role modulating ocean circulation and climate during the Cenozoic.

Formation of the Salar de Antofalla depression, Puna plateau, Argentina, by transient extension: an effect of lithospheric foundering

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Removal of dense mantle lithosphere is hypothesized to be an essential component of compressional orogenesis, yet the deformational effects of such removal and their timing and magnitude are debated. In the southern Puna plateau, Argentina, late Cenozoic foundering of mantle lithosphere is hypothesized based on thin modern mantle lithosphere, tomographic imaging of a dense mass in the asthenosphere beneath the orogen, and the spatial distribution and geochemistry of volcanic rocks. Thus, the southern Puna is an excellent location in which to study the effects of foundering on lithospheric strain. New field observations, mapping, and interpretive structural cross sections, together with published mapping and stratigraphic data, suggest that the Salar de Antofalla depression in the southern Puna was formed by a transient episode of tectonic extension that corresponded spatially and temporally with inferred lithosphere foundering.

The Salar de Antofalla depression is a sublinear, ~125 km long, NNE-trending topographic trough. We observed a tabular breccia bounding the western margin of the depression, which together with the relative ages of stratigraphic packages juxtaposed across the depression, suggests the Antofalla depression is an extensional halfgraben. The deformation history of the Antofalla depression is complex. Published paleocurrent orientations and growth strata indicate that the present location of the Antofalla depression was occupied by a basement-cored thrust belt with high topography relative to adjacent basins until the end of Early Miocene time. Evaporite and clastic deposition was initiated in a proto-Antofalla depression by the end of Middle Miocene time, suggesting that normal faulting began during Middle Miocene time. Some time later, a thrust kinematic regime was re-established, as documented by our mapping of compressionally-deformed Pliocene to Quaternary strata and published earthquake focal mechanisms that indicate E-W compression and subvertical extension. Therefore, extensional deformation that resulted in formation of the Antofalla depression was transient. The fault systems that accommodated extension and subsequent compression are subparallel, requiring a toggling between at least two kinematic regimes, rather than a single transition. Toggling between kinematic regimes has not been previously recognized in the southern Puna. Such toggling has been hypothesized to reflect foundering in other orogens and is difficult to explain in the southern Puna via a non-foundering mechanism.

Antofalla extension shows an interesting spatio-temporal relationship to subsequent slow normal/strike-slip faulting that has affected several areas of the southern Puna since Late Miocene time. Normal/strike-slip deformation and associated mafic volcanism, thought to be able to reach the surface only during non-thrust kinematic regimes, appear to define a radial migration away from the center of the Antofalla depression that occurred over 5-10 Myrs. We explore the implications of this pattern for foundering processes.

Potential top and lateral seals for supplemental CO_2 storage in Dunlin Group sandstones of the Tusse fault block, northern North Sea

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Top and lateral seals are imperative for subsurface containment of injected CO_2 during CCS operations. This is especially true for initial stages of the sequestration process because structural trapping delivers the primary CO_2 trapping mechanism. A full-scale CCS value chain is scheduled to be demonstrated along the Norwegian sector of the northern North Sea in 2024 under both Longship and Northern Lights projects. Injection of supercritical CO_2 will take place at the Aurora storage site in the Horda Platform, about 11 km south of the Troll West hydrocarbon field. Appraisal well 31/5-7 confirmed favourable storage conditions and previous geological assessments of the Aurora site. The storage complex is comprised of the Lower Jurassic Dunlin Group, where Johansen and Cook Formation sandstones are capped by lower permeability Drake Formation mudstones and shales. While confidence in storage potential at Aurora is fairly high, viability of the storage complex in nearby Horda Platform structures remains uncertain, particularly with respect to top and lateral seal potential. Assuming that CCS operations are demonstrated successfully at Aurora, further development of the Horda Platform as a European CO_2 storage hub will require a greater understanding of suitable traps and seals in the region.

As a contribution towards this effort, we present an assessment of top and lateral seal potential in the neighbouring Tusse fault block, approximately 8 km east of the Aurora, and underneath the producing Troll East field. Relevant stratigraphic horizons and faults are mapped from 3D seismic data and petrophysical data from regional boreholes are used to identify three potential closures, as well as characterize top seal presence and lateral seal types. Thickness mapping of the Drake Formation indicates the top seal decreases in thickness eastward from over 125 m to roughly 65 m, while log readings suggest favourable petrophysical properties throughout the study area. Each of the potential storage closures are dependent lateral fault seals, where the faults fall into two general populations. Within the Tusse fault block, thin-skinned intra-trap faults with throws less than 50 m create local juxtaposition seals, with the Drake mudstones downthrown onto Johansen and Cook sandstones. In contrast, larger trap-bounding faults with throws greater than 50 m are thick-skinned (e.g., the Tusse Fault Zone), and juxtapose thick, non-producing Upper Jurassic Viking Group sandstones (Troll reservoir) onto Dunlin Group sandstones in the footwall. These larger faults, therefore, must provide membrane seals that are continuous along these high-risk juxtapositions. Shale gouge ratio analyses indicate that zones where displacement is greater than 50 m are characterized by SGR values greater than 0.2, suggesting favourable membrane seal potential. Considering the compilation of the results herein, we infer that ample seals are present for utilizing the Tusse fault block as a supplemental Horda Platform CO_2 storage site, assuming good Dunlin Group reservoir quality within the study area and baring more detailed studies

Fracture network modelling in a carbonate reservoir of an old oil field: re-development or moving towards energy transition?

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The main purpose of building a fracture reservoir model is to obtain the petrophysical properties of faults and fractures upscaled to a simulation grid. These properties can be then integrated with the matrix petrophysical properties resulting in a dual-porosity/dual-permeability reservoir model. Fracture modelling is a challenging task due to the many uncertainties on the distribution and variability of the fracture network within the reservoir. Therefore, all the available data have to be critically analysed to build a consistent and robust conceptual model. Reassessment of old fields/discoveries made in fractured tight reservoirs implies to deal with the lack of information on reservoir, fluid and fracture network characteristics relying on alternative approaches. A modelling case from an old oil field (Benevento field, Southern Apennines of Italy) built of tight fractured carbonates is here presented.

The dataset is composed of three wells with cores and vintage well-logs, legacy 2D seismic lines, drilling and test data. Regional geological information from subsurface data in the surroundings is also available together with data from present-day seismicity and stress field. An integrated approach for fracture characterisation including structural core logging, well-log analysis, seismic interpretation and strain modelling, allowed to extract at best fracture information from the vintage dataset and to produce a multi-scale fault and fracture conceptual reservoir model. The defined input data were variously combined with the generated drivers for the multi-scenario fracture network modelling. The modelled fracture network cases were then calibrated and validated by dynamic modelling.

Reservoir fluids characterised by a gas-condensate mixture rich in CO_2 in supercritical state at reservoir conditions and high temperatures (130-150°C) at top reservoir (around 2500 TVDSS) are key to explore further potential of this structure in terms of carbon storage and geothermal exploitation making the Benevento field a suitable case for energy transition. As a consequence, besides the conventional applicability for reassessing the HC in-place volumes and steer the reappraisal/re-development strategy, the generated fracture model provides a base for simulation of CO_2 re-injection during production and EOR and it can also be used to understand and simulate hot water circulation within the aquifer at pre-feasibility study and geothermal potential assessment stage.

Strength evolution in fault rocks before and after seismic melting from Gangavalli fault zone, Southern India

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Catastrophic friction associated with rock melting, known as pseudotachylite, are innumerably found in the charnockites along the Gangavalli fault zone (GFZ), Southern India. Such brittle deformation in the upper crust is responsible for variable strength distribution across the fault zone. This paper investigates the evolution of strength in fault zone rocks before and after seismic melting. The samples have been categorized into deformed charnockite (i.e. D-charnockite) devoid of pseudotachylites and pseudotachylite bearing charnockite (i.e. Pt-charnockite). A distinct difference in the acoustic emission (AE) signatures is obtained from both samples indicating a more stable and dense Mogi type-III signature from Pt-charnockite. No significantly high AE energy is released from the D-charnockite during loading whereas Pt-charnockite show steady state of deformation. The average uniaxial compressive strength (UCS) value of Pt-charnockite is determined as 45.58 MPa which is almost double that of the D-charnockite with average UCS of 24 MPa. The obtained UCS have been compared with the fresh charnockite (average UCS 139 MPa) which reveal a drastic drop in compressive strength indicating a large earthquake in the past. Subsequent new slip surfaces are generated by earthquake pulses causing fluctuation in melt pressure and leads to a flip flop stress condition in the area.

Episodic evolution of a carbonate thrust zone in the Southern Pyrenees

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Field structural data combined with petrographic and geochemical analyses ($\delta^{13}C$, $\delta^{18}O$, $^{87}Sr/^{86}Sr$, clumped isotopes and trace elements) applied to calcite veins, fault rocks and host rocks are used to reconstruct the evolution of a thrust zone in the southern Pyrenees, and to qualitatively evaluate the thrust zone permeability. The studied thrust offsets the southern limb of the Sant Corneli-Bóixols anticline placing a Cenomanian-Turonian carbonate sequence on top of a Coniacian carbonate unit. Successive fracture systems and related calcite cements are interpreted to record: (i) an episodic evolution of the thrust zone, resulting from a process zone development and subsequent thrust slip propagation, and (ii) compartmentalization of the thrust system, leading to the migration of different fluids and to the formation of different vein systems in the footwall and in the hanging wall. In the footwall, three systematically oriented fracture systems, sealed by three calcite cements, and a chaotic breccia, cemented by the two former cements, developed. The formation of the two earliest fracture sets and the chaotic breccia is consistent with dilatant fracturing around the fault tip (in the process zone) during initial fault growth, whilst the formation of the latest fracture set suggests hybrid dilational-shear failure during thrust propagation. The successive fracturing events and related calcite cementation phases indicate that the structural permeability was transient and that fractures created new pathways for fluids but were rapidily occluded with calcite. Clumped isotope thermometry reveals a progressive increase in precipitation temperatures from ~50ºC up to ~117ºC. This fact is interpreted as progressive burial associated with thrust emplacement. During this period, the fluid system changed from meteoric fluids to evolved meteoric fluids likely due to water-rock interaction at increasing depths and temperatures. Contrary to the footwall, in the hanging wall only a crackle breccia is present. This breccia is cemented by a distinct calcite cement, which is also found in the thrust plane and in the fault core. This later cement precipitated from formation fluids, at ~95 ºC, that circulated along the fault core and in the hanging wall, again supporting compartmentalization of the thrust structure.

Structural evolution of a large-scale seismogenic fault in a magmatic arc: The Bolfin Fault Zone (Atacama Fault System)

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Understanding how major crustal-scale seismogenic faults nucleate and evolve in crystalline basement from the viscous to the brittle realm represents a long-standing, but still poorly constrained, target in structural geology and fault mechanics. Here, we addressed the spatio-temporal evolution of the Bolfin Fault Zone (BFZ), a >40-km-long seismogenic splay fault of the 1000-km-long strike-slip Atacama Fault System.

The BFZ has a sinuous fault trace cutting through crystalline rocks belonging to the Mesozoic magmatic arc of the Coastal Cordillera (Northern Chile). Evidence of ancient (125-118 Ma) seismicity is attested by occurrence of pseudotachylytes. Seismogenic faulting occurred at ~5-7 km depth and ≤ 270°C in a fluid-rich environment as recorded by extensive propylitic alteration and epidote-chlorite veining. Field geological surveys indicate that the BFZ nucleated along precursory 2-D anisotropies including well-developed magmatic foliation of plutons (northern and central segments) and andesitic dyke swarms (southern segment).

These precursory structures exploited by the BFZ were favorably oriented with respect to the long-term far-stress field imposed by the ancient oblique subduction. The large-scale sinuous geometry of the BFZ may result from linkage of these anisotropy-pinned segments during fault growth. We conclude that foliated plutons and dyke swarms play a pivotal role in controlling the nucleation, evolution and geometry of large-scale seismogenic faults in magmatic arcs.

Unravelling brittle faulting in time and space combining structural and X-ray diffraction analysis with K-Ar dating of synkinematic clay minerals. Examples from the central Apennines.

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Faults and fault zones are commonly characterized by the occurrence of syn-tectonic mineralizations and/or authigenic clay minerals, which testify to the presence and activity of geofluids during the possibly seismic deformation of faults. Such fluids are associated with the formation of mineralizations along faults (and in fault rocks) and with the formation of fault gouges in fault zones with associated formation of syn-kinematic minerals (e.g. clay minerals in fault gouge). Therefore, direct isotopic dating of these syn-tectonic precipitates (e.g. veins, authigenic illite in clay gouge) offer the potential to constrain the timing of fault activity in addition to forming a powerful tool to decipher complex and long tectono-thermal histories. When dealing with fault gouges formed at expense of Neogene rocks with strong terrigenous components, however, mixing between inherited and neoformed K-bearing minerals represents a significant obstacle that may even prevent constraining the exact age of brittle faulting. A successful solution is the application of the Illite Age Analysis (IAA) approach to several grain-size fractions of synkinematic illite for discriminating between the detrital and synkinematic components of the fault gouge.

We present two case studies of brittle deformation from the central Apennines (Zannone Island and Mt. Tancia) in which the potential of K-Ar dating of clay minerals in fault gouge (coupled with detailed structural analyses of fault zones and X-ray diffraction analysis of clay minerals) allowed us to 1) highlight and constrain the age for the innermost (i.e. oldest) thrust sheet of the central Apennines and 2) unravel the long-term tectono-thermal history of an extensionally-inverted thrust. Results are also used to confirm the potential of illite K-Ar dating to Neogen fault rocks formed at the expense of siliciclastic sequences.

Weak, Seismogenic Faults in the Lower Crust

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An estimate of the strength of faults is key to understanding the dynamics of earthquakes and lithosphere deformation. Within the shallow crust (<20 km) there is extensive evidence that high pore-fluid pressures and intrinsically-weak phyllosilicate minerals reduce the static effective frictional resistance to slip along faults to <0.3. For the continental crust to be seismogenic at depths >25 km, lower-crustal rocks should be relatively anhydrous, cold (<600 ^{o}C) and have no free water phase. These 'dry' conditions preclude water-based weakening mechanisms, implying that frictional resistance to slip on lower-crustal fault zones might be relatively high (~0.6-0.8). In this study, however, I demonstrate that sections of the Andean foreland are seismogenic from the surface down to ~40-45 km. Lower-crustal earthquakes are concentrated in the forelands of central Peru, southern Colombia and central Argentina, where shortening is occurring within pre-Andean Mesozoic rift systems. Estimates of the horizontal forces acting through the foreland lithosphere are <4-8 TN per metre along-strike, suggesting the seismogenic, lower-crustal faults support average shear stresses <150 MPa and have an average static effective frictional resistance to slip of <0.2.

Formation of a transform-parallel oceanic core complex along an inherited Timanian thrust, and impact on gas seepage in the Fram Strait

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The Vestnesa Ridge is a 4–5 kilometers thick sedimentary drift of contourites deposited by NW-travelling bottom currents over young oceanic crust (< 24 Ma) between Svalbard and the Molloy Ridge. The ridge trends NW–SE and parallels major transform faults in the Fram Strait (Spitsbergen and Molloy fracture zones). Along the southeastern portion of the ridge, brittle faults act as pathways for methane seepage on the seafloor, but the nature of these faults and their relationship with underlying crustal structures remain elusive.
Structural interpretation of seismic data reveals a set of curving, moderate-amplitude seismic reflections across the northwestern tip of the Vestnesa Ridge. Along the southwestern flank of the ridge, these reflections dip southwestwards and bound sequences of volcanosedimentary rocks extruded along the Molloy Ridge and the Molloy Fracture Zone during the opening of the Fram Strait (from ca. 24 Ma; Chron 6). Over the crest of the Vestnesa Ridge, these reflections are covered by relatively thin sediments and bend to sub-horizontal, thus defining an overall convex-upwards geometry. We interpret this set of convex-upward reflections to represent a major, bowed detachment bounding a NW–SE-trending oceanic core complex. Since this detachment bounds volcano-sedimentary rocks along the Molloy Fracture Zone, it likely formed early in the rift history, possibly during or prior to the onset of rift-related magmatism.
High resolution seismic data along the crest of the eastern portion of the Vestnesa Ridge show that most of the brittle faults responsible for methane seepage strike WNW–ESE to NW–SE, i.e., parallel to the southwest-dipping portion of the bowed detachment, and parallel to recently identified, several kilometers thick, inherited Timanian (ca. 600 Ma) thrusts in the continental crust of the Svalbard Archipelago. The Vestnesa Ridge notably aligns and coincides with the folded northwestern tip of the Kongsfjorden–Cowanodden Fault, a major top-SSW Timanian thrust that extends from Kongsfjorden in western Spitsbergen to central and eastern Spitsbergen, and continues farther east through the northern Barents Sea. Timanian faults like the Kongsfjorden–Cowanodden Fault are still active within the Svalbard Archipelago, possibly transferring transform tectonic movements in the Fram Strait into the Barents Sea crust (e.g., Storfjorden seismic sequence and related earthquakes in 2016 and 2019). Thus, it is probable that the crust beneath the Vestnesa Ridge is still partly exhuming (active oceanic core complex?) and that, in places, minor tectonic adjustments along the bowed detachment at depth triggered the formation of minor, subparallel, WNW–ESE- to NW–SE-striking faults in the overburden. This suggests coupling between crustal and near-surface deformation, which has important implications for fluid migration and seafloor methane seepage along the Vestnesa Ridge.

The origin of long, unsegmented, underdisplaced normal faults in the SW Barents Sea

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Normal faults accommodate stretching of the Earth's upper crust and can lead to the formation of extensional sedimentary basins. Our current understanding of normal fault growth can be seen as a spectrum; at one end is the 'propagating fault model', which proposes that faults grow by accruing length and displacement simultaneously, and at the other the 'constant length model', which suggests that faults do not start accumulating significant displacement until they reach their near-final lengths. Although, fault growth models have been discussed in literature for >30 years, these models are still debated, primarly because of an apparent conflict between models based on geometric properties of now-inactive normal fault populations versus those drawing on studies explicitly tracking fault growth using syn-depositional (growth) strata.

Here we test normal fault growth models using high-quality 3D seismic reflection data from SW Barents Sea, offshore northern Norway. These data image a fault network consisting of 15 Late Jurassic faults offsetting Early Triassic to Late Jurassic stratigraphy. The faults are unusual in that they are long (up to 42 km long), seemingly unsegmented (i.e. they lack clear along-strike changes in strike related to breached relays), demonstrably under-displaced (maximum 100 m displacement), and have anomalously high aspect ratios (>15). All faults are defined by broadly bell-shaped throw-length profiles. Larger faults appear to bound continuous (i.e. unsegmented), strike-elongate depocentres, the centre of which coincide with the location of maximum displacement on the bounding structures.

The geometry of these faults and their associated growth strata suggest they likely grew in a manner that closely follows the constant-length model. We propose that these faults represent fossilised examples of the very earliest stages of normal fault growth; in this case, the faults stopped accummulating displacement when they reached their final lengths, or soon afterwards. In this particular case, mechanical layering may have influenced fault growth and geometry, with ductile Triassic mudstones impeding downward propagation of the fault tips and the accummulation of displacement. Our observations may fill in a key gap on the global displacement-length scaling plots and could represent the missing link between the scaling relationships of individual earthquake ruptures, and scaling relationships typically defining large faults that grew over geological timescales.

Throw-rate variations within linkage zones during the growth of normal faults: Case studies from the Western Volcanic Zone, Iceland

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The growth of normal faults is generally described as a consequence of the linkage of either originally isolated fault segments during fault growth processes (isolated fault model) or individual fault segments that grow as kinematically-related components of a fault array (coherent fault model). Throughout this process, along-strike fault bends grow within the linkage zones in order to physically connect the previously isolated fault segments. However, it has been shown that throw and throw-rate values anomalously increase within fault bends, in response to local anomalies in the fault geometry and in order to preserve the horizontal strain-rate within the bend. Hence, we do not know how throw and throw-rates evolve within linkage zones during fault growth. We want to find whether the relationship between fault geometry and throw values applies over the entire process of fault growth, and so if it does affect the along-strike distribution of throw and throw-rates over the entire process of fault growth.

To do so, we investigated faults in the Western Volcanic Zone in Iceland, where the interplay between fault activity and lava flows offers the opportunity to study normal faults at a variety of different stages of fault linkage maturity. In Iceland faults ranges from cases where the principal fault segments are not physically connected (soft-linkage) to cases where the principal fault segments are connected with well-established fault bends (hard-linkage). Through detailed field mapping and field measurements of fault throws, normal faults are mapped and along-strike throw profiles are constructed in order to understand how the throw-rates relate with the local fault geometry along faults at different stages of linkage.

The results show that throw-rates increase within linkage zones and propagating fault bends independently from the stage of maturity of the fault bend. This implies that 1) the relationship between the local fault geometry and the along-strike distribution of throw-rate is driven by the deeper part of the fault, where established fault bends start propagating to the surface; 2) faults grow first by linkage and coalescence of separate faults, and then by accumulation of slip on the resultant fault, in agreement with models of fault growth by linkage and coalescence; 3) incipient fault bends can produce uncertainty associated with palaeoseismological results, if fault bends remain unrecognised. Moreover, this work demonstrates that existing models showing increased co-seismic and throw-rates within fault bends and sites of fault linkage found in continental extensional settings are valid in a geodynamic context of a mid-oceanic rifts.

Challenging displacement/length scaling laws and the use of global databases to understand the growth of normal faults

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The relationship between normal fault length and displacement has been widely researched over the past several decades. When plotted in log-log space, the two appear strongly positively correlated across several orders of magnitude. This empirical relationship is described by $Dmax=cL^n$, where D is maximum fault displacement, L is maximum fault-trace length, c is a constant, and n an exponent thought to fall within 0.5 to 2.0, with most studies suggesting 1-1.5. These n values come from global databases, which often used data in a way that was not intended to understand fault growth. We question the applicability of the data being used, and we believe that there are too many controls on D/L to have a one-size-fits-all scaling relationship. To address this, we have compiled a large global database of normal faults length and displacement that we have categorized by fault host-rock lithology, tectonic setting, maturity, and size. D/L scaling laws are helpful for forecasting true fault geometry in outcrop or seismic when only a 2D view is available. Furthermore, D/L scaling relationships are helpful when estimating strain distribution and have been used when developing models for fault growth, and understanding the geometrical distribution of faults and fractures in a petroleum reservoir.

There are two main hypotheses that we aim to address. The first hypothesis is that inapplicable or irrelevant data was used in previous D/L databases. Normal, strike-slip, and thrust faults are typically grouped together. Fault length and displacement are often taken from published maps where displacement was not specifically given, often taken from interpreted cross-sections. Throw is often plotted as displacement (or vise-versa), which could slightly change D/L scaling relationships. Occasionally, data was mis-interpreted, for example, original sources listed fault height or distance between faults, which was later used incorrectly to measure fault length or displacement, or deformation bands and fractures were included as tectonic faults. Our second hypothesis is that factors such as fault host-rock lithology, tectonic setting, maturity, and size affect fault growth. We believe that better scaling laws and our general understanding of normal fault could be improved by quality checking data, separating by fault type, lithology, tectonic setting, and fault maturity.

Researchers in the field agree that factors such as lithology, tectonic setting, and regional strain likely affect fault kinematics, but the extent to which they affect D/L scaling laws has not been investigated. We address these questions by creating a database of normal fault length, displacement, and timing, along with lithology, tectonic setting, and a range of other factors from outcrop studies, analogue models, and 2D and 3D seismic from >2200 normal faults from >50 previous works. We found a general scaling law of Dmax=.05L0.98. We also find that while most host rock lithologies do not significantly affect the relationship between length and displacement, volcanic rocks are under-displaced by up to an order of magnitude and sedimentary rocks with evaporites are slightly over-displaced. This is the first attempt at a comprehensive, integrated study of these factors on normal fault growth. Our new database of normal fault properties demonstrates that one-size-fits-all scaling relationships are overly simplistic and that D/L scaling relationships should not be used indiscriminately.

Fault-bend folding in extensional settings: throw variations and strain partitioning.

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Normal faults have irregular geometries on a range of scales arising from different processes including refraction and segmentation. In this study, a quantitative model is presented for the throw variations and strain partitioning associated with fault-bend folding along normal faults. The main feature of this model is that nonplanar normal faults display variations in discontinuous and continuous throw that are complementary and are accommodated by faulting and folding respectively. This model shows that small-scale normal and reverse drag arise from fault bends that steepen or shallow downwards, respectively.
The model highlights how fault throws are partitioned between continuous (i.e. folding) and discontinuous (i.e. discrete offset) strain along fault bends for the full range of possible fault dip changes (Fig. 1). It illustrates the potential significance of strain partitioning on fault throws, the most common measure of normal fault displacements, and the potential errors arising from not accounting for the continuous strains accommodated by folding and bed rotations. We show that fault throw measurements can be subject to errors of up to ca. 50% for realistic down-dip fault bend geometries (up to ca. 40°) on otherwise sub-planar faults. This effect will provide irregular variations in throw and bed geometries that must be accounted for in associated kinematic interpretations.

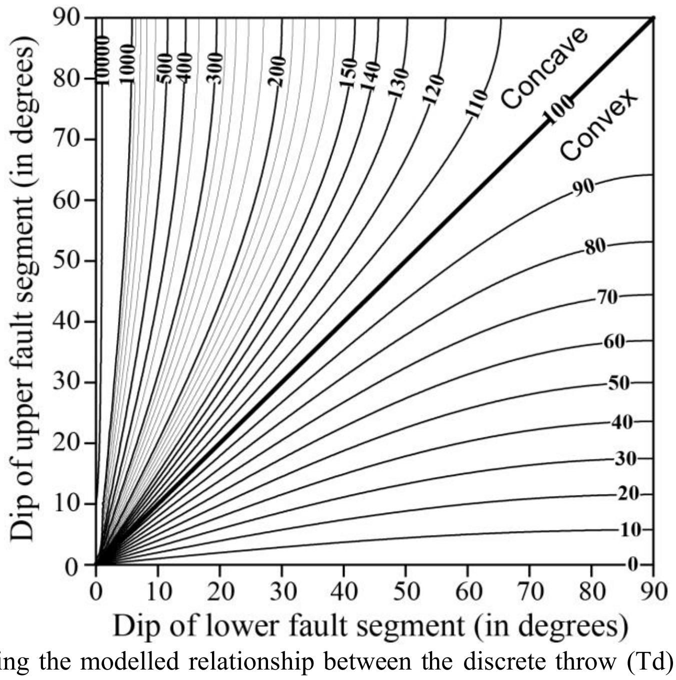

Figure 1. Graph showing the modelled relationship between the discrete throw (Td) as a proportion of the total throw (Tt), and the dips of the lower and upper fault segments of a sharp fault bend that comprises only two fault segments.

Stress-transfer modelling of dual-stage gold emplacement at the Obuasi deposit, Ghana

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Emplacement of gold at the supergiant Obuasi deposit is interpreted to be coeval with a transition from compressional to transpressional regional tectonics during the late Eburnean orogeny. Aftershock-driven seismogenic control on gold emplacement at Obuasi is examined graphically using these two discrete regional stress fields. The deposit occupies an ~8km section of the northeast striking Obuasi fissure, a regional scale thrust fault with sinistral strike-slip reactivation, and a section of the younger north striking strike-slip Ashanti fissure. Previous researchers have established two distinct styles of economic mineralisation present in the district: disseminated gold-bearing arsenopyrite-dominated sulphides, and free-milling gold hosted in small (up to 25mm wide) quartz veins. These are attributed to a dual-stage mineralisation history, with earlier sulphide-hosted gold emplaced during NW-SE trending shortening (D1) and later native gold emplaced during strike-slip reactivation (D2), as a response to NNW-SSE to N-S-directed shortening. Modelled using published present day fault geometries, elevated Coulomb stresses transferred following a universal 0.1m sinistral strike-slip event under D2 stress conditions show good spatial correlations with gold grades >1 g/t (Fig.1). Dilational jog structures at the deposit exert first order control on the distribution of transferred Coulomb stress. Comparing analagous links between elevated Coulomb stress values and aftershock-enabled fluid flux, a seismogenic control for the distribution of gold during D2 is implied. Under D1 contraction conditions, modelled Coulomb stresses following a 0.1m reverse slip show poor correlation with high gold grades, potentially indicating absence of aftershock sequence control, or modelling shortcomings attributed to multiple deformation events affecting fault geometries.

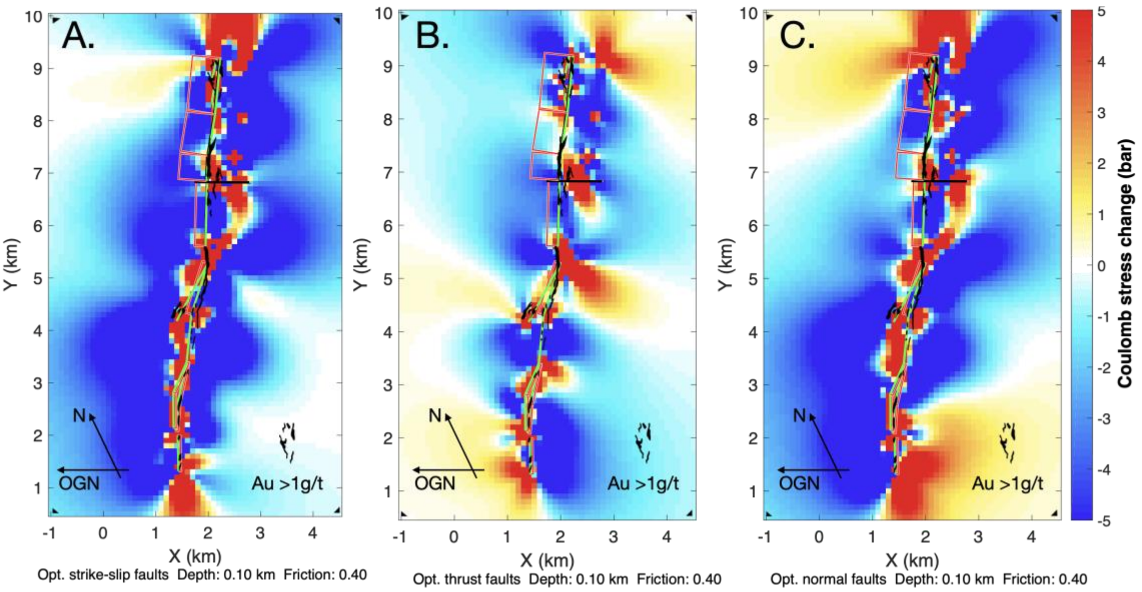

Figure 1. Calculated Coulomb stress change following 0.1m sinistral strike-slip movement under D2 NNW trending regional stress, resolved on optimised (A) strike-slip, (B) thrust, and (C) normal faults, with overlay of gold grades >1g/t. Obuasi Mine Grid North and Grid North indicated.

A DFN approach to understand the behaviour of fluid flow in fractured rocks

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Fractured rocks are one of the largest resources on the earth's surface. In the subsoil these rocks host many of the most important reserves of water, oil and natural gas, and can also be exploit for the storage of gas or carbon dioxide. Many oil, gas, geothermal and water reservoirs place in fractured rocks.

In this context one of the most complex objectives is to represent the distribution of fracture systems in these rocks, developing numerical models that describe the fracture networks and the physical processes that govern them.

Usually the Discrete Fracture Network (DFN) properties, derived from models are used to populate equivalent continuum porous models at reservoir scale. This method reduces computational times but does not explicitly represent the properties of individual fractures, such as connectivity and spatial distribution. This also influences the result in terms of distribution of fluid and liquid pressure inside the rock.

In this work, through the realization of about 600 DFN models, we related the increase in fracturing intensity (P32) with the physical parameters that govern the relationship between fluid flow and fracture systems, such as number, volume, porosity, and permeability of fractures. Furthermore, by simulating the injection of CO_2, the flow pathways and the migration of fluids within fracture systems in a compressive domain are reconstructed.

This method allows to model at different scale and in different geological settings the fracture systems, using exclusively a DFN approach.

The potential role of stylolites in gold mobilization and deposition

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Orogenic gold deposits are generally thought to be regions where gold has been concentrated and deposited by metamorphic fluids within veins and fault zones. According to Groves et al. (2020), a major source of the gold-rich fluids can be attributed to the prograde metamorphic dewatering of chlorite and the breakdown of pyrite to pyrrhotite in subduction zones. These fluids pond in the Sub-Continental Lithospheric Mantle, before being channelled up through major faults zones, with gold deposited in lower order faults. Ligands allow gold to become soluble, but its solubility is influenced by pressure, temperature, pH, eH, oxygen fugacity, Fe and As concentration. Currently, most of the research focuses on these high flux, episodic fault pumping events, and passive, continuous and low fluid-flow processes acting in between these extreme events are poorly documented. Here, we investigate samples from the Chinese gold deposits in West Qinling and Jiaodong, and in particular mineralised samples from outside the primary gold-bearing fault zones. Preliminary observations point to stylolites and Pressure Solution Seams (PSS) as potential features playing a role in the inter-seismic redistribution of gold. This work aims to determine the extent to which pressure solution and its associated structures play a role in the mobilisation and/or deposition of gold and its associated sulfide phases. During pressure solution, does gold behave like an insoluble- or a soluble phase? This study uses high resolution/large area backscatter electron imaging and X-ray microtomography to characterise the role of pressure solution creep in mineralized samples and, in particular, collect evidence for the behaviour of gold in the inter-seismic periods.

Structural Controls on the Cavanacaw Gold Vein Deposit, Northern Ireland: Late-Scandian Deformation in the Grampian Terrane of Ulster and Implications for Metallogeny in the Laurentian Caledonides

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The Cavanacaw gold-silver-lead deposit in Country Tyrone, Northern Ireland, is one of several orogenic gold vein deposits hosted by the Laurentian Caledonides of Ireland and Scotland. Previous studies interpret the Cavanacaw deposit to have had a complicated geological history: the broadly N-S trending sinistral vein system is inferred to have initiated during the Grampian and to have mineralised through the injection of several fluid pulses during the Palaeozoic (Siluro-Devonian and Carboniferous) (Cliff and Wolfenden, 1989; Earls et al., 1996; Parnell et al., 2000). These studies further document broad similarities in paragenesis and fluid chemistry to infer a temporal link between Cavanacaw and the nearby Curraghinalt deposit. The localisation of the Cavanacaw deposit is specifically attributed to the deep-seated, NNE-SSW trending Omagh Lineament, which is interpreted to have a pre-Caledonian origin as it is spatially related to a significant strike swing in the hosting Dalradian rocks (hereafter, the 'Sperrin Knee Bend') (Earls et al., 1996; Parnell et al., 2000). Here, we present a new genetic model for the Cavanacaw deposit based on geological observations and the detailed structural analysis of historic trench maps. This model is notably simpler than what has previously been proposed.

We demonstrate that the vein system at Cavanacaw is hosted by a broadly N-S striking dextral fracture network that propagated within an overall NE-SW striking sinistral shear zone system. This sinistral shearing was evidently progressive, with the later increments of shearing rotating the veins and hosting rock anticlockwise in the south of the deposit. Regionally, we further demonstrate that the formation of the Sperrin Knee Bend is compatible with the progressive sinistral shearing within the NE-SW shear zone system. The timing of this 'lock up' is dated through a minor calc-alkaline suite that intruded within the extensional domain of this shear zone system (426.69 ± 0.85 Ma; Cooper et al., 2013). This, coupled with the structural model developed, broadly confines the propagation of the Cavanacaw vein system to the late-Scandian event of the Caledonian orogeny (c. 425 to 395 Ma) (e.g. Dewey and Stratchan, 2003).

Despite the interpretations of previous studies (e.g. Earls et al., 1996; Parnell et al., 2000), the structural model presented for Cavanacaw demonstrates that the deposit is younger than the nearby Curraghinalt deposit, which is now respectively constrained to a post-orogenic 'collapse' episode following the Grampian event (c. 462.7 to 452.8 Ma) (Rice et al., 2016; Shaw et al., in prep). Instead, we highlight that the vein system at Cavanacaw propagated under a common palaeostress field to the Cononish, Croagh Patrick, and Clontibret gold vein deposits in the Laurentian Caledonides.

Paleostress reconstruction of brittle deformation in the forland part of the West Congo Belt, Republic of Congo and Republic Democratic of Congo

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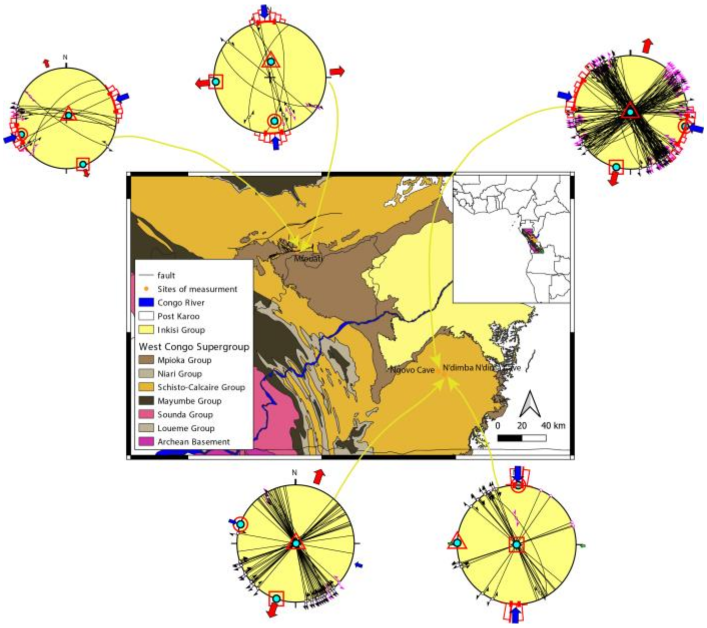

The West Congo Belt is the african counterpart of the well-kown Araçuaí-West Congo belt that formed during the assembly of West Gondwana. Despite increasing tentative unravelling of the structural and the tectonic evolution of the West Congo Belt, few studies have focused on the kinematics of the long post-orogenic evolution (500 Ma) successively encompasses the Gondwana intraplate, South-Atlantic rifting and passive margin contexts. As deformation was mainly in the brittle domain, we conducted a fault-slip analysis and paleostress inversion. Previous results were obtained for the Kinshasa-Brazzaville region, in Cambrian-Ordoviciea sandstones and now we present new results on the foreland of the West-Congo Belt in the two Congo's. It displays several strike-slip brittle shear zones that strike perpendiclar to the orientation of fold axis of the mobile belt. These shear zones developped differently oriented strike-slip fault populations, some of which apparently conjugated (NW-SE, NE-SW and W-E). Most of these faults develop damage zones, well exposed in karstic caves. Several kinematic indicators were used for the reconstruction of the stress field, such as tension fractures in linking damages zones and horstail fractures. "Tree structures" or opposite orientated tension fractures at tip damage zones helped to determine reactivation within faults. The majority of faults patterns controled the fluid flow circulation which precipated calcite or iron along their fault surfaces. Stress inversion using the Win Tensor pogram allow us to determine σ_1 brittle deformation (Fig. 1) σ_1 oriented in pure strike-slip regime with oriented N-S

Figure 1 : Map of the study area showing the different tensor identified in RDC and RC.

Characterization of sub-seismic resolution structural and diagenetic heterogeneities in porous sandstones

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Deformation bands and structurally related diagenetic heterogeneities, here named Structural and Diagenetic Heterogeneities (SDH), have been recognized to affect subsurface fluid flow on a range of scales and potentially promoting reservoir compartmentalization, altering flow paths, influencing flow buffering, and sealing during production. Their impact on reservoir hydraulic properties depends on many factors, such as their permeability contrast with respect to the undeformed reservoir rock, their anisotropy, thickness, geometry as well as their arrangement and physical connectivity in the subsurface. Deformation bands offsets (from a few mm to 20-40 mm) and diagenetic heterogeneities (carbonate nodules) dimensions (from 0.2 to 15 m in length; from 0.1 to 1.0 m in thickness) make them SDH below seismic resolution.

We used Ground Penetrating Radar (GPR) for detection and analysis of the assemblage "deformation bands - carbonate nodules", in high-porosity arkose sandstone of the Northern Apennines (Italy). Petrophysical (air-permeability) and mechanical (uniaxial compressive strength) properties of host rock, deformation bands, and calcite-cement nodules were evaluated along a 30-meters thick stratigraphic log to characterize the permeability and strength variations of those features. 2D GPR surveys allowed the description of the SDH spatial organization, geometry, and continuity in the subsurface. The assemblage "deformation bands – nodules" decreases porosity and permeability and produces a strengthening effect of the rock volume, inducing a strong mechanical and petrophysical heterogeneity to the pristine rock. Different textural, petrophysical, and geomechanical properties of deformation bands, nodules, and host rock result in different GPR response (dielectric permittivity; instantaneous attributes).

We show that GPR can be useful to characterize variations in petrophysical and geomechanical properties other than characterize the geometry and spatial distribution of flow baffles and small-scale flow barriers in the subsurface such as deformation bands and cement-nodules. GPR showed its worth as a high-resolution and non-invasive tool to extend outcrop information (petrophysical and geomechanical data) to 3D subsurface volumes in a way to reconstruct detailed and realistic outcrop analogues. Such potential could be critical in assisting and improving the characterization of SDH networks in the study of faulted aquifers in porous sandstones.

Multiscale fracture density analysis at Stromboli Volcano, Italy: implications to flank stability

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Stromboli volcano has experienced four sector collapses over the past 13 thousand years, resulting in the formation of the Sciara del Fuoco (SDF) horseshoe-shaped depression and an inferred NE / SW striking rift zone across the SDF and the western sector of the island. These events have resulted in the formation of steep depressions on the slopes on the volcano where episodes of instability are continuously being observed and recorded. This study aims to quantify the fracture density inside and outside the rift zone to identify potential damaged zones that could reduce the edifice strength and promote fracturing. In order to do so we have carried out a multiscale analysis, by integrating satellite observations, field work and seismic and electrical resistivity analyses on cm scale blocks belonging to 11 lava units from the main volcanic cycles that have built the volcano edifice, ie. Paleostromboli, Nestromboli and Vancori. 0.5 m resolution Pleiades satellite data has been first used to highlight 23635 distinct linear features across the island, determine fracture density across the island and isolate key areas of weakness on the volcano. Data collected from aerial observation has shown that the SW of the island including the summit area and the slopes of SDF have higher average fracture density of 5.279 $x\ 10^{-4} m^2$ in contrast to the rest of the volcano. Density, porosity, P- wave velocity in dry and wet conditions and electrical resistivity (in wet conditions) were measured via an ultrasonic pulse generator and acquisition system (Pundit) and an on purpose built measuring quadrupole on cm scale blocks of lavas collected from both within and outside the proposed rift zone to assess the physical state and the crack damage of the different lava units. Preliminary results show high variability in P-wave velocity with 2.5 km/s < Vp < 5km/s as well as in electrical resistivity with 21.7 < ρ < 590 Ohm * m. This is presumably due to the lavas texture and the variable content of bubble/ vesicles porosity and crack damage, that is reflected by an effective overall porosity between 0 and 10 %. Further work will assess crack density throughout optical analyses and systematically investigate the UCS and elastic moduli. This integrated approach is expected to provide a multiscale fracture density and allow to develop further laboratory testing on how slip surfaces can evolve to a flank collapse at Stromboli.

Lineament network in the flysh mountain belts: the Gorce Mts. case study

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The presented study is focused on the geometrical and topological aspects of the lineament network identified in the Gorce Mts. (the Western Outer Carpathians, Poland). The Outer Carpathians are built mainly of Cretaceous to Paleogen flysh, which were deposited in the deep sea basins separated by ridges. These deposits were folded and thrusted as sequence of several nappes during Miocene.The lineament network was digitized from the high-resolution LiDAR digital elevation model of the area.

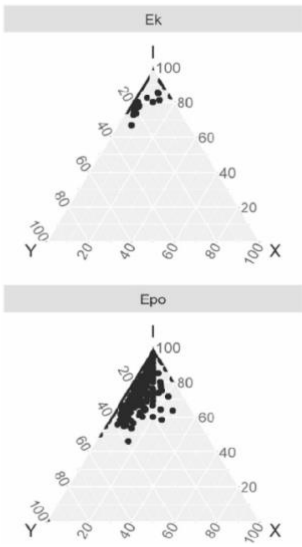

Fig. 1. Nodes type plot of two units with different interconnection characteristics (Ek – Kowaniec beds, Epo – Piwniczna Sandstones)

Lineaments network, containing over 500 features was categorized by lithostratigraphic unit key, to check, if the different units differ in the structural style. The topology of the network was analysed with NetworkGT ArcGIS toolbox by Nyberg et al., 2018. Both, topological and geometrical parameters of the network were then analysed statistically in the whole area as well as in the selected units.

We found, that the LiDAR imagery can be applied as source data for such an analyse, however with some limitations. These limitations are in the main part presence of observer-related bias. On the other hand, these data are the new quality in structural analyses of areas such as the Western Carpathians.

The topology of the lineament networks changes both in N-S and W-E profile. The first change is due to changing lithostratigraphic units, which react differently to stress; the E-W trend is an effect of a regional-scale fault zone cutting the area. In general, the Gorce Mts. structural network is of isolated type. However, in the members composed mainly of resistant, thick-bedded sandstones, instead of dominating flysh packets, are more interconnected (Fig. 1).

In general, presented work, which was one of the first attempts of application of combined topological-geometrical analyses in the flysh-type mountains showed that there is potential in such a methodology. Moreover, the NetworkGT was found to be highly useful in topological analyses, however, the input data should be prepared with such analyses in mind.

References:

Nyberg, B., Nixon, C.W., Sanderson, D.J., 2018. NetworkGT: A GIS tool for geometric and topological analysis of two-dimensional fracture networks. Geosphere 14, 1618–1634. https://doi.org/10.1130/GES01595.1
Kania, M., Szczęch, M., 2020. Geometry and topology of tectonolineaments in the Gorce Mts. (Outer Carpathians) in Poland. Journal of Structural Geology 141, 104186. https://doi.org/10.1016/j.jsg.2020.104186

Precision and Accuracy of Digital and Analogue Compass-Clinometers

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Structural measurements using digital compass-clinometers offer more rapid acquisition, easier backup, and convenient integration with other field data. Systematic empirical testing of eight Apple smart-phones and tablets was carried out, alongside a variety of analogue compass-clinometers (all with a 'traditional' free-swinging magnetised compass needle), and cross-checked against survey measurements based on long sight-lines (> 800m) and calibrated inclinometers. A standardised procedure was followed carefully to calibrate the digital devices prior to each test. Tests measured the dip and strike of planes and the plunge and azimuth of lineations, across a range of orientations.

While analogue compass-clinometers are able to measure orientations repeatedly and reliably with an accuracy of ±5° or better, the performance of the digital devices was highly variable and unpredictable, raising significant doubt about their suitability for geological field measurements. In some tests the Apple devices performed adequately, with an accuracy of ±5°, while in other tests, measurements showed a range of over 30°. The underlying cause(s) of the variability is unclear. Most of the spread is in the strike component (i.e. measurements from the digital compass), corroborating other results that show that digital inclinometers are able to measure dip with high accuracy. Further testing is needed using larger numbers of geologists with a wider range of different digital devices and software apps.

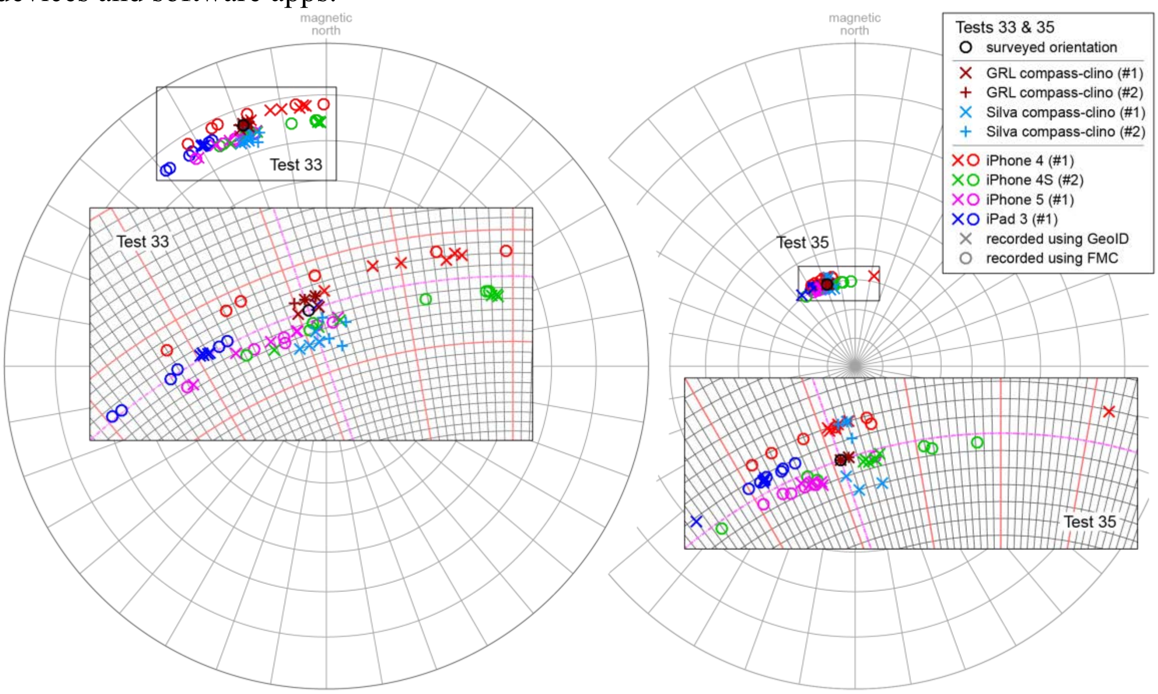

Figure: Examples of test results using a number of different analogue and digital compass-clinometers, plotted as poles to planes on a lower hemisphere equal-angle stereonet (grid on main nets is 10°; insets show a 1° net with 10° grid lines in red).

Hot tip: On the relationship between sheet intrusion tip-shape and stress

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Magmatic sheet intrusions are fundamental to the formation of Earth's crust. Inferences to the mechanisms of sheet emplacement have been largely built on field observations, but these observations are exclusively of a magmatic system that did not grow beyond their observed state: they record intrusion death, not growth. Classical models for intrusion involve elastic-brittle tensile splitting of the host rock, and conform to linear elastic fracture mechanics. Numerous recent studies have highlighted examples of ductile deformation ahead of the intrusion tip, where host rock failure occurs through shear deformation. Elastic splitting is typically associated with bladed or sharp-elliptical tips, whereas shear failure commonly associates with blunt superelliptical tips. Here we use finite element simulation to model variably-shaped crack tips, to show the effect of sill tip geometry in controlling stress concentrations, and the likely pathways for sheet propagation. Stress concentration is strongly affected by the radius of tip curvature. Sharp-tipped segments are efficient at concentrating stress, and should grow even with a minor magma overpressure. The maximum stress concentration is in plane with the sill, and the models predict coplanar sill growth. Elliptical to superelliptical tips are less efficient at concentrating stress, and would therefore require more substantial magma overpressure to grow. For elliptical sills, the maximum stress remains in plane. Superellipses exhibit curvature minima that are non-coplanar to the sill; the distance out of plane is controlled by how squared the tip region is. We propose that tip geometry is important in the propagation pathway of sheet intrusions, the mechanics of sheet growth, and the style and distribution of resulting host rock deformations. Models seeking to consider these factors will be critically dependent on the prescribed intrusion tip geometry; a preferred alternative should be to allow the tip to evolve naturally during growth and arrest.

Emplacement and propagation mechanisms of magma fingers

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Magma transport in large volcanic plumbing systems is often described to occur via networks of channel-like sheet intrusions (i.e., dykes and sills). In many cases, elongate, finger-like geometries emerge from the outer margin of these planar sheet intrusions during magma migration through the Earth's crust. Previous field studies and both analogue and numerical experiments suggest that magma finger emplacement is dominated by either i) fracture propagation (mode I failure), ii) shear failure (mode II failure), or iii) viscous deformation (e.g., host rock fluidisation). In this study, we present field-based data collected at the outer margin of the Paleogene Shonkin Sag laccolith, Montana, USA, to evaluate how host rocks (Cretaceous Eagle sandstone) deform to accommodate magma finger emplacement. We combine unmanned aerial vehicle (UAV or drone) photogrammetry surveys with field observations to map and quantify host rock deformation and to assess whether or not magma finger emplacement can be described by a single end-member process.

Our field observations show that magma finger emplacement at the outer margin of the Shonkin Sag laccolith was accommodated by all three proposed end-member models. We predominantly observe brittle deformation, folding and shear failure between adjacent magma fingers, whereas evidence for host rock fluidisation is mainly observed at the cross-sectional lateral tips of magma fingers and to a minor extent at the top and bottom intrusion-host rock contacts. Preliminary results of photogrammetric analyses suggest that overburden strata uplift due to magma finger inflation accommodates up to 20% of the intrusion thickness. It is important to note, that we often observe all three modes of deformation mechanism in the same outcrop at metre scale and in some cases associated with a single magma finger. This metre-scale variation of host rock deformation indicates that magma finger emplacement is likely accommodated by multiple deformation mechanisms.

We conclude that host rock fluidisation in combination with brittle, ductile and elastic deformation accommodated magma emplacement at the outer margin of the Shonkin Sag laccolith. We further hypothesise magma fingers were potentially initiated due to host rock fluidisation and resulting viscous fingering. The propagation and growth in length, however, might be dominated by i) fracture propagation, ii) viscous indentation, and/or iii) host rock fluidisation, highlighting that emplacement mechanisms might change during magma emplacement. We relate brittle deformation, folding, and shear failure between adjacent magma fingers to a compressional regime that forms once fingers grow in width, resulting in host rock shortening and thickening.

Lower crustal buoyancy and viscosity controls on deformation localization during crustal extension

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It is well known that variations in relative viscosities within the lithosphere influence modes of strain localization during continental extension. Geothermal gradients and the depth of the Moho strongly affect lithospheric strength profiles, and hence the degree of strain localization during extensional deformation. Here we report results of a parametric study on how variations in relative viscosities and crustal thickness influence the buoyancy of the lower crust and the degree of strain localization during extension using the Underworld Geodynamics numerical modelling code. The relationship between buoyancy forces and the mechanical resistance of the lithosphere is characterized by the dimensionless Argand number (Ar). The degree of the coupling between brittle upper-crustal layers and lower-crustal viscous layers, which determines the degree of strain localization, is characterized by an Integrated Strength parameter (I). We investigate the interplay between both parameters using the Ar/I ratio. In nature, the geothermal gradient will determine the viscosity profile of power-law rock and mineral rheologies in the ductile parts of the lithosphere. This is approximated in our isothermal numerical experiments by multiple layers with depth-varying Newtonian viscosities. This implementation allows a quantitative assessment of the viscosity contrasts that drive lower crustal flow over a range of crustal thickness.

Buoyancy-driven isostatic ascent of lower crustal material is observed in experiments with high Ar/I ratios, which results in the formation of wide extensional basins. The Ar/I ratio depends on the depth of the Moho and the thermal structure. One of the main factors that influences the Ar/I ratio is the effective viscosity at the top of the lithospheric mantle. In our experiments, the presence of a large strength contrast at the Moho inhibits both lateral flow of the lower crust and localization of extensional strain. A reduction in resistance forces is obtained by increasing the thermal gradient and/or the Moho depth, which weakens the lithospheric mantle and promotes the isostatic ascent of lower crust, respectively. Lower crustal flow is observed in experiments in which the viscosity at the top of lithospheric mantle is $< 10^{23}$ Pas. The relative thicknesses of the brittle upper and ductile lower crustal layers also determine the Ar/I ratio and the structural architecture. When the weak lower crustal layer is thick, voluminous crustal flow drives rapid, localized isostatic ascent to form metamorphic core complex structures. Here the Ar/I ratio will be larger compared to a hot, relatively thin lithosphere, or a cold lithosphere with a slightly thicker brittle upper crust. The correlation between the relative crustal thickness and the viscosity contrast at the Moho constrained by the Ar/I ratio determines the magnitude of lower crustal flow and the different modes of strain localization.

The influence of laterally varying crustal strength on rift physiography – Insights from 3D numerical models

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Continental rifts form across a mosaic of crustal units, each unit displaying properties that reflect their own unique tectonic evolution and lithology. Areas containing numerous and pervasive structural heterogeneities comprise multiple sites where strain may localise and can be considered relatively weak. In contrast, relatively pristine areas of crust, such as igneous batholiths, contain few heterogeneities and may be considered relatively strong. Rift physiography is largely reflective of the properties of the underlying crustal substrate, including the distribution of any heterogeneities. However, characteristic rift physiographies associated with 'strong' and 'weak' crust, and how the physiography of the rift changes where these areas are juxtaposed remain elusive.

Here, we use the 3D thermo-mechanical numerical code ASPECT to investigate how areas of differing upper crustal strength influence rift physiography. We extend a 500x500x100 volume, within which we define four 125km wide upper crustal domains of either 'strong', 'normal' or 'weak' crust. Crustal strength is determined by randomising the initial plastic strain in the model across 5km blocks, larger contrasts between adjacent blocks provide more sites for strain localisation and therefore weaken the domain.

Our modelling simulations reveal that strain rapidly localises onto high-displacement structures in the weak domain. Fault spacing and the strain accommodated by each fault decreases in the normal domain, with the strong domain characterised by closely-spaced, low displacement structures. When heterogeneities are incorporated into the strong domain, strain rapidly localises in these areas, producing widely spaced faults surrounded by low-displacement structures. Furthermore, we find that faults, initially inhibited at the boundaries of the weak domain, propagate outwards into the adjacent stronger domains.

We determine characteristic rift physiographies associated with highly heterogeneous (i.e. weak) and relatively pristine (i.e. strong) areas of crust, and show how rift physiography varies when these properties change laterally. Our observations have important implications for the development of rift systems globally, the Corinth and Lake Tanganyika rifts both develop at high angles to heterogeneous basements. The Great South Basin, New Zealand, developed perpendicular to basement terranes incluing a strong granitic batholith and potentially weak sedimentary forearc basin. Observations from the Great South Basin suggest that rift physiography varies between terranes and that faults inhibition occurs at the boundaries with stronger areas of crust, similar to observations made here.

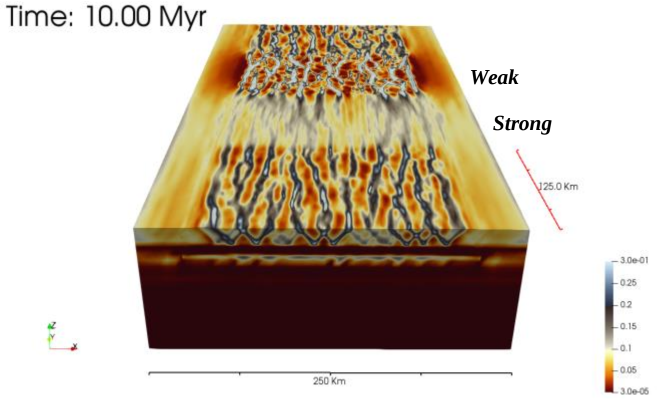

Figure 1 – Model showing non-initial plastic strain accrued after 10My. Note the well estiablished faults in the weak domain and the diffuse strain in the strong domain

Late to post-orogenic structural configuration in the westernmost Bohemian Massif and SE Germany

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Current regional tectonic models suggest a SW extension of the Saxothuringian Zone (Central European Variscan domain) across the western Bohemian Massif border fault zones into southern Germany, where it is covered by Permian-Mesozoic sedimentary rocks. This model is based on observed similar Variscan units in the Bohemian Massif to the east and the northern Black Forest (Schwarzwald) and Vosges to the west and the assumption that exposed units are laterally connected over 350-400 km distance. Although Saxothuringian units and structures are well studied in the exposed parts of the orogen, the extent and geometry of orogenic units (allochthons and autochthons) and structures in the covered parts of the assumed Saxothuringian zone in SE Germany is unknown.

In this study we investigate the possible SW extension of Variscan units and structures and their spatial relationship underlying Permian-Mesozoic sedimentary cover in SE Germany. We use the recently acquired Franken 2D seismic survey (ca. 230 km) and reprocessed DEKORP (85-4N and 3B-MVE90, ca. 220 km) profiles and integrate available information from exposed Saxothuringian zone and wells. The seismic profile DEKORP 85-4N strikes NW-SE perpendicular to the main trend of the exposed Variscan units and images the entire crust. The cross cutting DEKORP 3B-MVE90 profile images exposed Variscan units to the NE and crosses the Variscan border fault zone (Franconian Fault Zone, FFZ) and images Permian-Mesozoic sedimentary cover overlying Variscan units to the W/NW. The latter profile links DEKORP 85-4N to the Franken seismic grid and enables interpretation and correlation of buried and exposed Variscan units across FFZ.

Interpretation of seismic reflection profiles and their correlation with exposed Variscan units and structures show that Variscan allochthons (equivalent of the Münchberg nappe) and underlying metasedimentary rocks extend ca. 30-35 km to the W/SW of the FFZ. Variscan décollement/shear zone translating nappe units imaged as high amplitude and dipping reflections reach to the base of sedimentary cover to the W/SW. Observed décollement/shear zone most likely shows that top-to-the west/southwest tectonic transport occurred during the Variscan assemblage. Units in the footwall of the décollement/shear zone are correlated to exposed Early-Carboniferous parauthochthons (low grade flysch). The observed geometry of the interpreted décollement/shear zone (locally concave up) is likely related to the late and post-orogenic deformation phases. Our results help to improve the understanding of Variscan tectonics and can be applied to other ancient and modern orogenic settings worldwide.

Interplay between gravity-driven and strike-slip deformation in Upper Neogene sediments, Gulf of Moattama, offshore Myanmar

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The Gulf of Moattama, offshore southern Myanmar is a sedimentary depocentre west of the southern extension of the Sagaing Fault, an active strike-slip fault with the Present-day dextral motion of around 1.8 cm/yr accommodating c. 50% of the northward motion of India and western Myanmar with respect to SE Asia. The deepest part of the Gulf of Moattama accommodates over 10 km thickness of Upper Miocene to Recent sediment largely supplied by the deltas of the Ayeyarwaddy and Salween rivers. In the thinner, northern part of the depocentre the Sagaing Fault is well imaged as two narrow, sub-vertical major fault zones. But passing to the south, where the depocentre thickens, the traces of the principle displacement zones of the Sagaing Fault become obscured in complex arrays of minor, predominantly extensional faults. Yet, the overall tectonic picture is that the displacement on the Sagaing Fault continues south of the depocentre, where it is involved in a regional-scale pull-apart geometry involving the Andaman back-arc spreading centre, and the West Andaman-Sumatran fault system. Structural geometries within the Gulf of Moattama revealed on Pliocene-Pleistocene seismic horizons, comprise distributed deformation over a large area at apparent releasing splays of the Sagaing Fault zone. Important structural features include multiple, closely-spaced, ENE-WSW to E-W trending normal faults and narrow zones of strike-slip faults and folds. Some normal faults have curved 3D geometries characteristic of growth faults common in thick deltaic deposits. In a complex region of faulting, Early Pliocene horizons show predominantly NNE-SSW to WNW-ESE fault strikes, while the dominant strike directions are E-W to ENE-WSW at shallower Pliocene horizons; although a few, larger faults have persistent NNE-SSW orientations across all horizons. Local transtension and transpression are observed along a narrow zone of syngenetic growth normal faults and anticlines. These distinct structural geometries are interpreted to result from the interactions between strike-slip and gravity-driven deformation in thick deltaic deposit underlain by overpressured shale detachments. Key structural characteristics of the Gulf of Moattama were replicated by sandbox modelling, including broadly distributed normal faults at strike-slip fault tips; strike-slip reactivation of the lateral boundary of a delta deposit; and decoupling of sedimentary cover from a basement strike-slip fault. The region illustrates an unusual range of interacting structural styles where strike-slip deformation ranges from being fully coupled to deformation in the sedimentary basin, to being highly decoupled.

A review of geological and geophysical evidence for major inverted faults at shallow depth beneath the Vale of Glamorgan coast, South Wales, UK.

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There is significant evidence for major ENE-WSW striking geological structures beneath the Vale of Glamorgan coast, including reactivated faults, folds and a regional unconformity. Our review combines evidence for the structures, which would otherwise be missed by sole consideration of either onshore or offshore data.

The assemblage of data includes information on the geometry and kinematics of faults through striation analysis; shallow magneto-metric and sedimentological surveys; deep geophysics such as reflection, refraction, and seismic mapping, together with detailed measurement of coastal outcrop. Corroborative palaeontological data also yield evidence for major structures, with local fault splays striking NW-SE through Whitmore Bay and Jackson's Bay, Barry, amongst other localities close by. Particular attention is drawn to the Lower Carboniferous zones of coral species as biostratigraphic markers to determine estimates of displacement upon these partially covered local fault splays.

The combined evidence reveals a significantly new model for the Vale Coast structures and with further investigation and comparisons of coastal outcrop and legacy seismic data west of the Vale, the style of deformation along this Heritage Coast may present a useful analogue for the structure offshore Gower.

The regional structural framework of both Palaeozoic and Mesozoic strata, however, is complicated by N-S and NW-SE lateral and oblique ramps which are part of the Variscan thrust-fold belt and the Mesozoic Bristol Channel Basin; therefore, along strike correlation is hindered by these compartmentalising faults. Nevertheless, through careful deduction, Mesozoic negative inversion of the faults beneath the Vale Coast and their implied continuation westwards across Swansea Bay, has allowed significant space for Upper Carboniferous strata, worthy of exploration, to be accessible at shallow depth adjacent to both the Vale and Gower coasts.

Furthermore, our ongoing mapping of coastal outcrop around the Bristol Channel borderlands supports most of the findings within decades of prolific literature produced by many geological scholars. In particular, we demonstrate finally that the occurrence of Tertiary positive inversion of Mesozoic normal faults, common in north Devon and Somerset, is also true for the history of the Vale Coast structures.

Analogue modelling of rift segment interaction in orthogonal and rotational extension: implications for the East African Rift

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During extension of the continental lithosphere, rift basins develop. These rift basins are often initially offset, and must interact and connect in order to create a continuous rift system, that may ultimately achieve break-up. When simulating extensional tectonics and rift interaction structures, tectonic modellers often apply a continuous extension rate along the strike of a rift (system). Yet in nature, extension velocity variations occur along rifts and plate boundaries since plates move apart about a pole of rotation. This results in rotational extension, causing rift propagation and structural gradients. Here we therefore present analogue experiments of rift interaction structures to compare the effects of orthogonal extension versus rotational extension conditions.

Our modelling efforts show that rotational extension and orthogonal extension produce significantly different large-scale structures. Rotational extension can cause significant changes in rift maturity between rift segments, delay rift interaction zone development, and make rift segments propagate in opposite directions (both towards and away from the rotation pole). Still local features in a rotational extension system can often be regarded as evolving in an orthogonal extension setting. Furthermore, we find that various degrees of rift underlap produce three basic modes of rift linkage structures. Low underlap distance experiments develop rift pass structures. With increasing underlap distance, transfer zone basins develop. High degrees of underlap tend to result in en echelon sub-basins. Our results match with data from previous modelling efforts and natural examples. We furthermore propose a large-scale tectonic scenario for the East African Rift System based on the effects of rotational extension and associated rift propagation observed in our models (Fig. 1). These insights may also be applicable when studying other large-scale rift systems (e.g. the South Atlantic).

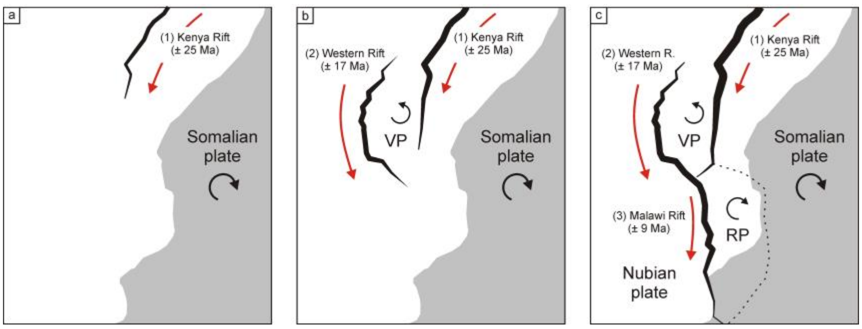

Figure 1. Evolution of the East African Rift System as inferred from analogue models (Zwaan & Schreurs, 2020).

REFERENCES

Zwaan, F., Schreurs, G. 2020. Rift segment interaction in orthogonal and rotational extension experiments: Implications for the large-scale development of rift systems. J. Struct. Geol. https://doi.org/10.1016/j.jsg.2020.104119

Applying Tectonics&StructuralGeology to fault displacement hazard analysis: examples from reverse earthquake ruptures

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Fault displacement hazard (FDH) is the hazard deriving from coseismic faulting of the ground surface during earthquakes. This can damage buildings and facilities located on or close to the trace of the ruptured fault. FDH is particularly relevant for long infrastructures (e.g., lifelines) and critical facilities (nuclear facilities, dams, etc.). Coseismic ruptures can occur along the trace of the main fault, responsible for the release of most of the seismic moment (i.e, Principal Fault rupturing, PF) and along structures away from the PF trace, connected or unconnected to the PF (i.e., distributed ruptures, DR). DR can occur on faults that despite being secondary to PF, have their own geologic and geomorphic expression, and therefore are mappable before the earthquake. More often, DR reveals as small discontinuous ruptures poorly predictable in their location an amount of displacement, with concentrations in structural complexities of the PF (step-overs, bends, gaps) or in zones of deformation related to earthquake folding (flexural slip, bending-moment faulting).

FDH can be mitigated by strategies of fault zoning and avoidance. When FDH cannot be avoided, such as for pipelines, or when an active fault is discovered after building construction, probabilistic approaches can help in estimating the likelihood of occurrence and expected amount of surface displacement during an earthquake at the site of interest, which can be on or off the PF trace (e.g., Petersen et al., 2011, BSSA, doi: 10.1785/0120100035, with references). A critical issue in the process concerns the probability of displacement on poorly predictable DR. A feasible solution can be found in empirical "attenuation regressions" based on dense datasets of well documented historic earthquake surface ruptures.

We present an analysis of reverse faulting surface ruptures based on a widened version of the SURE worldwide surface ruptures database (Baize et al., 2019, SRL, doi: 10.1785/0220190144) enriched with a "ranking" action aimed at distinguish the PF (rank 1) from different types of DR depending on their structural relation with PF, such as simple (unpredictable) DR, DR on mappable secondary faults connected to PF, fold-related DR (bending-moment, flexural-slip), and triggered (or sympathetic) DR on faults not connected to PF (Nurminen et al., 2020, Frontiers in Earth Science, doi: 10.3389/feart.2020.581605). This approach allows us to define regressions that can account for the tectonic setting of the earthquake fault. The results are empirical regressions of DR, which can be used to determine the conditional probability of exceeding a displacement value on a possible DR crossing a site of interest located at a distance "r" from the trace of a reverse active fault.

Active faulting and deep-seated gravitational slope deformation in carbonate rocks (Central Apennines, Italy)

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Abstract

Active faulting and deep-seated gravitational slope deformation (DGSD) constitute common geological hazards in mountain belts worldwide. In the Italian Central Apennines, km-thick carbonate sedimentary sequences are cut by major active normal faults which shape the landscape generating intermontane basins. Previous geomorphological observations suggest that the mountains slopes affected by DGSD are often located in the fault footwalls.

We selected five mountain slopes affected by DGSD and exposing the footwall of active seis normal faults exhumed from 2 to 0.5 km depth of active normal faults. We combined field structural analysis of the slopes with microstructural investigation of the slipping zones from the major and secondary slip surfaces. The interpretation of this dataset shows that DGSDs exploit pre-existing surfaces formed both at depth and near the ground surface by tectonic faulting and, locally, by gravitational collapse. The slipping zones of the fault surfaces are more texturally mature (i.e. well-developed ultracataclasites/cataclasites vs. cataclasites/protocataclasites), because of the larger displacement accommodated. The widespread traces of clasts indentation within the cataclastic matrix is consistent with clast fragmentation, fluid-infiltration and congruent pressure-solution mechanisms active at low ambient temperatures and confining pressures and, possibly, low slip rates (creep).

We conclude that in carbonate rocks of the Central Apennines, DGSDs commonly exploit pre-existing tectonic faults/fractures and, in addition, localize slip along newly formed fractures that accommodate deformation mechanisms similar to those associated to seismic faulting. Furthermore, the exposure of fault surfaces along mountain slopes in the Central Apennines is the result of both surface seismic rupturing and DGSD.

Earthquake Induced Landslides and Liquefaction: 24 January 2020 Sivrice (Elazığ) Earthquake, East Turkey

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The East Anatolian Fault (EAF) is a major left-lateral strike-slip fault that extends about 550 km in eastern Turkey. On 24 January 2020, a devastating Mw 6.8 earthquake occurred in the Pütürge segment of the southern (main) section of the East Anatolian Fault (EAF), Turkey (17:55 UTC, 38.360 N, 39.060 E, 8.06 km deep, Disaster & Emergency Management Authority, Presidential of Earthquake Department (AFAD)). This article presents the preliminary results of comprehensive study on mapping of the distribution of landslides, lateral spreading and other ground damaged effects triggered by the Sivrice earthquake occurred on the East Anatolian Fault. I conducted on-ground field survey immediately after Sivrice earthquake to document the general distribution and extend of landslides, lateral spreading, and to seek evidence of primary surface fault rupture (surface displacement) generated by this earthquake: (1) The Sivrice earthquake produced fewer landslides than empirical prediction for shallow earthquakes of these magnitudes; (2) the Sivrice earthquake triggered extensive lateral spreading in Holocene age river banks; (3) Sivrice earthquake did not produce primary surface rupture.

Regional deformation and offshore crustal local faulting as combined processes to explain uplift through time constrained by investigating differentially-uplifted Late Quaternary palaeoshorelines: the foreland Hyblean Plateau, SE Sicily.

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Abstract

Quaternary uplift is well documented in SE Sicily, a region prone to damaging seismic events, such as the 1693 "Val di Noto" Earthquake (Mw 7.4), the largest seismic event reported within the Italian Earthquake Catalogue, whose seismogenic source is still debated and, consequently, the long-term seismic hazard is poorly-understood. However, the spatial variation in the timing and rates of uplift are still debated, so it is difficult to link the dominant tectonic process(es) responsible for the uplift and the location of seismogenic sources. To better constrain the uplift rate, we have refined the dating of Late Quaternary marine terraces, using a synchronous correlation approach, driven by both published and newly obtained numerical age controls ($^{234}U/^{230}Th$ dating on corals). This has allowed re-calculation of uplift rates along a N-S oriented transect within the Hyblean Plateau (HP) foreland region. Consequently, we have mapped the geometry of palaeoshorelines along a coastline-parallel transect, and hence the rates of uplift. The results suggest increasing uplift rate from south to north across the HP, and that uplift rates have remained constant through the late Quaternary. This spatially-changing but temporally constant uplift places constraints on the proportion of uplift produced by regional geodynamic processes versus produced by local faults, such as an offshore E-dipping active normal fault. We discuss these new findings in terms of the long-term seismic hazard for one of the most seismically-active regions in the Mediterranean Basin.

Evidences of Active Tectonics in Nazira-Naginimora area in the Frontal Part of Naga Thrust, North-East India

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Convergence of Indian Plate with Burma Plate led to the development of number of thrusts. These thrust-sheets of the Belt of Schuppen are undergoing incessant compression. This led to the active tectonic deformation of the Quaternary sediments in front of the Naga Thrust. The thrust system of the Belt of Schuppen has led to several dislocations of the river flow pattern. It is observed that the shifting is unidirectional i.e. towards the NW-SE direction. In the process of shifting, the meandering river has left a suite of visible meander scars on the landscape. Naga thrust has pronounced effect on the frontal zone of the Belt of Schuppen. The splaying and ramping of the thrusts along with many strike-slip faults caused many deformations in the recent time. In this study presence of tectonic activity around the Nazira basement low is evidenced by different quaternary deformational features. These effects were clearly observed in the quaternary alluvium, especially on the banks of the river. Dikhow river which has undergone many geomorphologic changes due to these tectonic processes, carries such proofs along both banks. Deformation of the quaternary sediments and change in the attitudes of the beds across the river banks are the major indications of the active tectonics. Different structures and features on the soft older to newer alluvium indicate that the alluvium is undergoing deformation since Late Pliocene. Moreover, channel migration caused many abandoned palaeochannels which also underwent the same tectonic circumstances. The presence of earthquake epicentres depict that the area is tectonically active. Using of satellite imageries, epicentral plot and gravity anomaly data provides deformational signatures of the recent past associated mostly with Naga orogeny.

Keywords: Naga thrust, Palaeochannels, alluvium

Presenting geological data for seismic hazard assessment input

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In order to improve seimsic hazard assessment (SHA), we need to include fault data. As fault-based seismic hazard modelling becomes more sophisticated, there is need for detailed and accurate fault data to be provided in an accessible way such that it can be easily and appropriately incorporated into seismic hazard models. In addition, the uncertainties in the priary data need to be reported so that the uncertainties in transforming data into models can be calculated.

We present a database schema that provides a structure for formulating fault data for use in fault-based seimsic hazard calculations. This format allows data to be extracted and be used as direct input into existing open source seismic hazard calculation codes. The fault maps are provided at three levels of complexity from traces at the primary observation level to faults and master faults that can be utilised in models. Different interpretations of master faults can be explored. We provide a framework for providing the relative location and activity certainties for each level of mapping. We provide local surface geometry data and a simple format so uncertainties can be extracted. We provide location-specific slip-rate measurements, including the data used to calculate them. Such site-specific details allow uncertianties in slip-rate propagation along faults and their implications for calculated recurrence rates to be determined.

We show fault maps and data for the central Apennines, Italy, a region of continental extension. The master fault maps contain 43 or 44 individual master faults (depending on the choice of master fault configuration), which comprise 89 faults and 312 traces. There are 149 point measurements of slip-rate, 290 and 254 measurements of slip vector azimuth and plunge respectively, and 468 and 490 point measurements of surface strike and dip.

We show how the database can be used to infer calculations of earthquake hazard and risk. We can use the data to compare the relative contribution to the hazard and risk at specific sites from individual faults and suggest a methodology and communication strategy for this.

Structural style of the frontal fold-and-thrust belt and syntectonic mineral vein evolution at the Chachas area in the Western Cordillera (Central Peruvian Andes)

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The Andes, with their abundance of vast and complete outcrops, make a perfect tectonic laboratory. However, the researchers so far focused mainly on tectonic analysis on continental and regional scales; time-consuming and labor-intensive mesotectonic field measurements are not commonly found in the literature. In this study, we aimed to reconstruct the structural evolution of the Mesozoic strata in the Frontal Fold and Thrust Belt of the Western Cordillera in southern Peru, based on field observations and measurements, detailed structural analysis, and microscopic vein analysis.

The applied approach enabled us to identify several stages of intense tectonic deformation related to bivergent thrusting in the Western Cordillera with accompanying structures that could be produced by the NE-SW Eocene (Inca phase) and Miocene (Quechua phase) compression. We correlated reported compressional and extensional stages with the multiphase evolution of mineral veins. We believe that at least some of the crust growth in the Western Cordillera may be related to a significant shortening of Mesozoic sedimentary complexes due to intense frontal fold-and-thrust tectonic processes. To the east, the intensity of folding and thrusting decreases, suggesting that observed shortening might be related to a very localized and narrow zones in the Western Cordillera.

Paleoseismicity of the NE Bohemian Massif: insights from Th-U dating of damaged speleothems and collapsed karst chambers (Niedźwiedzia Cave, Poland)

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In the tectonically stable part of Europe, singular events strong enough to produce fault rupture have been recorded so far. One of such the early Holocene earthquakes has been documented along significant, ca. 200-km long, tectonic line in Central Europe - Sudetic Marginal Fault (SMF). Less than 20 km south of the SMF in the Niedźwiedzia Cave, several dozen broken and fallen stalagmites, stalactites, and flowstones have been documented, the largest of which are nearly 0.6 m in diameter and around 2 m in height. Often, there are also massive underground collapses of thickness, reaching up to several meters. Multiphase speleothem damage and cave passage collapse were dated with U-series methods, revealing five breaking events: (1) 320-306 ka, (2) 253-236 ka, (3) 162-158 ka, (4) 135-132 ka, and (5) >21 ka. Events 1, 3, and 4 are robustly constrained, whereas events 2 and 5 are of less certainty.
The damage occurred independently from climatic conditions both in cold and warm periods; hence frost and ice activity can be likely excluded. Observed damage of the cave ceiling, walls and also the floor points that deformations might be earthquake effect. To quantify the probable seismic source size, we compared a scant record of historical and prehistoric earthquakes from the region with ground motion models and speleothem failure criteria.
The proximity of the SMF and documented earthquakes M>6 in the Late Pleistocene and Holocene points to the conclusion that the SMF can produce peak ground acceleration (PGA) amplitudes at a distance between the fault and the cave, forcing the speleothems to break.
Plausible seismogenic sources are faults limiting the Upper Nysa Kłodzka Graben from the east. Although there is no historical data that would help estimate the seismic hazard herein, the short distance between the cave and faults (from several hundred meters to 8 km) would reduce the attenuation effect and even moderate earthquake suffice to damage speleothems. Reported Th-U dated events of in-cave collapses are the first Middle to Late Pleistocene geochronological-documented marks of paleoseismic activity at the northern flanks of the Bohemian Massif.

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GPS measured deformation and associated surface strain patterns in the Garhwal – Kumaun region in the Northwest Himalaya

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Himalayan mountain ranges formed due to the collision between India and the Eurasian plates and have been known as one of the seismically active zones over the globe. The continuing collision results stress accumulation throughout the Himalayan arc which eventually releases small to moderate magnitude earthquakes. Here we investigate the present-day deformation and associated strain rates in the Garhwal-Kumaun region of the NW Himalaya which lies in the central seismic gap.
Continuous observations of GPS data from 37 stations (35 continuously operating stations and 2 campaign stations), from IGS (International GNSS Service), and Wadia institute local network for a span of 8 years from 2010 to 2017 were used in this study. The data were processed using the GAMIT/GLOBK software version 10.6 in itrf08_comb reference frame and the velocities were estimated on both ITRF and the Indian reference frame. Crustal strain rates in the region were calculated from the available GPS data using the modified least square approach. The local strain rates at each grid node are estimated and a weight function is used for the error reduction.
GPS measured site velocities in the Indian reference frame indicate that all the stations are showing velocities towards the south and their magnitude is less in the case of frontal Himalaya. Velocities estimated in the Indian reference frame show that the subsurface detachment fault MHT is locked in the frontal part of the Himalaya. The shortening rate of Indian crust is estimated by taking the residual velocity between Haridwar (HARI) station situated at the south of HFT and Panamik (PAN2) station in the Eurasian plate. Estimated rates show a 15.46 ± 1.97 mm/yr crustal shortening in the mobile belt.
Strain rate analysis shows the existence of four types of surface deformation zones in the region and termed as 1) High compressional strain zone in the vicinity of MCT at Higher Himalaya. 2) Purely extensional strain regime at sub-Himalaya in the proximity of the Moradabad fault. 3) Zone of equally partitioned compressional and extensional strain rates in the eastern part of the Kumaun Himalaya. and 4) Isolated zones of abysmally low strain rates. Majority of earthquakes in the Himalaya are observed across a ~100 Km wide zone (HSB) where thrust fault mechanisms are dominated with a NNE-SSW dipping nodal plane which corresponds the high compressional strain zone. However, in the west of Chamoli region curvilinear strain pattern is observed which is notably different from the expected surface strain distribution pattern of the India plate movement. That shows the shear deformation is predominant in this region which can be linked with the free fluid aided shear movement along the dipping mid crustal ramp of the MHT. In general, we expect NNE-SSW compressional strain distribution in the Himalaya, that allinged with the India plate movement. However extensional deformation zone is also observed in the frontal part of the Kumaun Himalaya where many active thrust faults namely, Dhikala, Pawalgarh are present along with the NE-SW oriented transverse Moradabad fault. The GPS measured SW movements of the frontal active faults elucidates that strain transfer is taking place from the highly compressional MCT zone towards the extensional frontal Himalaya along the detachment fault MHT. This supports the proposition of frontal propagation of southern plate boundary fault systems in a convergent margin.

Characteristics of Surface Rupturing Earthquakes in the Walker Lane, USA from Centimeter Scale Imagery & Paleoseismic Trenching

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Centimeter scale drone based structure from motion orthoimagery was collected shortly following the 2019 M6.4 & 7.1 Ridgecrest and 2020 M6.5 Monte Cristo Range (MCRE) earthquakes in the western USA. In total, 7 paleoseismic trenches were excavated in the Fall of 2020 along all three ruptures. Fractures are mapped at high detail for tens of km along each rupture. Despite similarly ruptured materials and tectonic settings, each rupture displays distinctly different characteristics in not only the overall rupture pattern, but also finer scale fracturing. Ridgecrest ruptures are primarily confined to a few main traces, while MCRE are frequently discontinuous fields of numerous distributed cracks. Here examples of these different patterns are presented. Paleoseismic trenches reveal evidence of past surface rupturing events along each fault, and show distinctly different surface rupture widths, fracture patterns, and rupture character.

Present-day geodynamics of the Western Alps: new insights from earthquake mechanisms

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Due to the low to moderate seismicity of the European Western Alps, few focal mechanisms are available to date in this region, and the corresponding current seismic stress and strain fields remain partly elusive. The development of dense seismic networks in the past decades now provides a substantial amount of seismic records down to low magnitudes. The corresponding data, while challenging to handle due to their amount and relative noise, represent a new opportunity to increase the spatial resolution of seismic deformation fields.

The aim of this study is to quantitatively assess the current seismic stress and strain fields within the Western Alps, from a probabilistic standpoint, using new seismotectonic data. The dataset comprises more than 30,000 earthquakes recorded by dense seismic networks since 1989 and more than 2200 focal mechanisms newly computed in a consistent manner. The global distribution of P and T axes plunges confirms a majority of transcurrent focal mechanisms in the overall alpine realm, combined with pure extension localized in the core of the belt. We inverted this new set of focal mechanisms through several strategies, including a seismotectonic zoning scheme and grid procedure, revealing extensional axes oriented obliquely to the strike of the belt. The Bayesian inversion of this new dataset of focal mechanisms provides a probabilistic 3D reconstruction of the style of seismic deformation in the Western Alps. Extension is found clustered, instead of continuous along the backbone of the belt. Compression is robustly retrieved only in the Po plain, which lays at the limit between the Adriatic and Eurasian plates. High frequency spatial variations of the seismic deformation are consistent with surface horizontal GNSS measurements as well as with deep lithospheric structures, thereby providing new elements to understand the current 3D dynamics of the belt.

We interpret the ongoing seismotectonic and kinematic regimes as being controlled by the joint effects of far-field forces –imposed by the counterclockwise rotation of Adria with respect to Europe- and of buoyancy forces in the core of the belt, which together explain the high frequency patches of extension and of marginal compression overprinted on an overall transcurrent tectonic regime.

Towards understanding the nucleation of earthquakes: Partition of seismic and aseismic slip during a shallow crust earthquake swarm

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How earthquakes initiate and run-away into major ruptures is still a challenging research topic, that will benefit from increasing our capability to observe processes from the seismogenic source regions. In recent years, two models for earthquake nucleation have been proposed to explain earthquakes sequences, a slow-slipping model and a cascade model, based mostly on the analysing seismic data. Here we use geodetic data to contribute to the study of seismogenic source regions during earthquake sequences. Earthquake swarms are unusual as they do not obey observational physics laws, e.g., Gutemberg-Richter law. This deviation might be to a disproportioned contribution of aseismic processes, and hence provide with an opportunity to investigate the role of aseismic behaviour in the nucleation and propagation of earthquakes.

Here, we study a shallow seismic swarm in Nevada, USA, in 2011. We process satellite radar image to form differential interferograms and to quantify the surface displacements. From the analysis of the interferograms, we observe a clear surface displacement signal (~4 cm in line-of-sight direction) consistent with slip along a N-S striking normal fault, before the largest magnitude event in the swarm. We also find that interferograms across the largest event (M4.7) are dominated by slip on a NE-SW striking fault. Thus, we consider slip along a fault system with a geometry consisting of two fault planes. To interpret the surface displacement in terms of fault slip, we invert for its optimal geometry directly using the interferometric wrapped phase (Jiang and González, 2020). Based on the fault geometry together with inferred surface ruptures, we construct a smooth fault plane with triangular dislocations. Then, we extend our previous method to obtain distributed fault slip models from the wrapped phase. We implemented a physics-based linear elastic crack model with no stress singularities, coupled with a linear time inversion with optimal regularization method to estimate the temporal evolution of fault slip. We apply this method to the 2011 Hawthorne swarm geodetic data to test the two conceptual earthquake nucleation and propagation models. The inversion revealed (1) two slip maxima; a narrow (1 km2) slip area on the southern fault with high average slip (0.8m) occurring before the M4.7 event; and a wider (40km2) slip area on the northern fault which ruptured during and after the M4.7 event and with lower average slip (0.1m); (2) our results are more consistent with a cascade model of discrete slip patches, rather than a slow-slipping model thought as a growing elliptical crack; (3) the aseismic (geodetic) moment ratio is variable from 100% before the M4.7 event, but remained larger than 60% after it.

The study of the 2011 Hawthorne swarm allows us to illuminate fault slip in much greater detail than usually possible. We conclude that there was significant aseismic fault processes, most likely slow-slip or localized fluid-enhanced fault slip, along with discrete segments of the fault plane active before and after the largest earthquakes in this swarm. This study contributes to highlighting the importance of using geodetic data to understand the role of aseismic processes in the nucleation and propagation of earthquakes.

Cooking synthetic rocks in the laboratory: preparing "sandstones" with known microstructural attributes

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Regardless of their composition and microstructure, sandstones in the Earth's crust are subject to a variety of geological processes and deformation mechanisms. However, microstructural attributes play a key role in the manner and extent to which sandstones react to these hydraulic and mechanical processes. Therefore, understanding the influence of microstructural geometries on the hydromechanical behaviour of sandstones is necessary to improve model predictions, which are routinely used in many aspects of geoscience and engineering. While studies using theoretical or experimental approaches have successfully provided a good understanding of the key control of microstructural parameters such as porosity on the hydraulic and mechanical properties of sandstones, the deconvolved influence of the multitude of microstructural parameters remains unclear. This is because, for natural rocks, differences in porosity are often accompanied by differences in other microstructural parameters, such as grain or pore size. Until now the study of the role of a specific microstructural attribute in isolation has relied heavily on numerical modelling, without the necessary experimental validation. To address this shortcoming, we created precisely controlled synthetic samples by sintering glass beads. The sintering process allow us to control porosity and grain size independently, so that we could deconvolve these microstructural parameters and parameterise specifically for their importance. Our results demonstrate that the trends in porosity, permeability, and P- and S-wave velocity for our synthetic samples are similar to those reported for natural sandstones. Moreover, the mechanical behaviour of the synthetic samples is similar to that of natural sandstones. We were able to reproduce the typical failure modes of sandstones in our synthetic samples during compression tests: brittle failure at low confining pressure and the transition to a ductile failure mode at higher confining pressure, including the formation of compaction bands. Our study thus demonstrates the possibilities that lie in creating synthetic samples using sintering and opens up new perspectives for unravelling the contribution of microstructural attributes on the mechanical and hydraulic properties of granular rocks such as sandstones.

Dynamic Compressive Strength and Fragmentation in Rocks

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Brittle deformation in rocks depends upon loading rate; with increasing rates, typically greater than ~10 s^{-1}, rocks become significantly stronger. Strengthening 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. Consequently, the products of high strain rate brittle failure are highly fragmented. In nature, deformation at high strain rate conditions is uncommon but extremely hazardous; restricted to impact events, some landslides, and supershear fault rupturing. The ability to identify the products of dynamic failure in the geological record may be important for constraining the kinematics, dynamics, and hazards associated with these high-energy geological events. In this study, we aim to characterise the behaviour and fragmentation of rocks under dynamic loading conditions.

We have chosen a variety of lithologies to characterise dynamic brittle deformation: granite, gneiss, sandstone, limestone, and marble. Mechanical data and samples for subsequent analysis were obtained using a triaxial loading frame (10^{-7} – 10^{-4} s^{-1}) and a Split-Hopkinson Pressure Bar (SHPB; 10^{0} – 10^{3} s^{-1}). Our results demonstrate dynamic strength increases with lithologically-controlled characteristic strain rates from 144 s^{-1} to 322 s^{-1}, where larger characteristic strain rates are associated with higher porosity lithologies. Characterization of the resultant rock samples show a progression of increasing fragmentation with increasing strain-rate. The degree of fragmentation as a function of strain is also lithologically dependent. Scaled or not, our fragmentation results are inconsistent with current predictions from theoretical models. Nevertheless, our results can be readily parameterised for use in geodynamical models of rock failure.

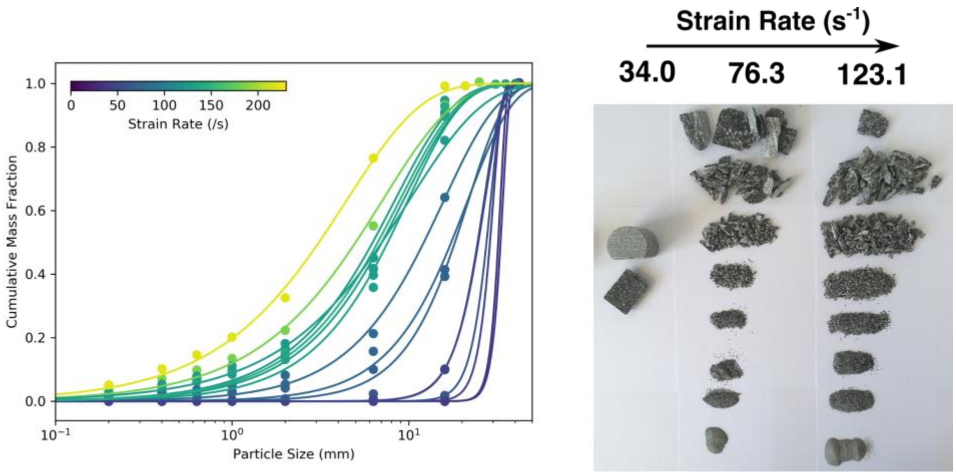

Figure 1: Fragment size distributions of experimentally deformed gneiss. Sieve measurements (points) are fitted with Weibull distributions, coloured by strain rate.

Decoding deformed sandstones: an assessment of rock microstructure using X-ray microtomography, image analysis and multivariate statistics

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An understanding of rock microstructure is crucial when it comes to determining the nature of deformation. The microstructure of poorly sorted flysch sandstones remains challenging to decipher as their microstructural trends are usually hardly traceable. However, close 3D insights into rock microstructure are currently possible with the use of high-resolution X-ray microtomography (μCT). The imaging of a rock's interior, when followed by image analysis and statistical methods allows for tracking even the most gentle deviations in rock fabric. Therefore, this contribution aims to evaluate the microstructure of a flysch sandstone sample to identify the potential trends reflecting a possible deformational fabric.

The study object is a medium-grained flysch sandstone (Krosno Fm., Carpathians), which was collected from a damage zone of a local detachment horizon with numerous and relatively thin (<0.5 mm) compaction bands. On the macroscopic scale, it seems that the studied sample is devoid of them. The sample was subjected to μCT scanning with the resolution of 12 μm. We used Fiji software for image analysis and processing and R software for statistical analyses. Neither the grains of quartz and feldspars nor the surrounding matrix were included in the analysis as they are not distinguishable in the μCT scan. The remaining rock components were segmented and assigned with a set of variables by means of image analysis. The set comprises 38 variables describing mineralogical properties, size, shape, spatial distribution and orientation of the mineralogical components. Within the scanned rock volume of 1 cm^3, over 20,000 components were detected. Based on their mutual similarities expressed by the variables, they were clustered into 4 groups. These groups represent micas, heavy minerals, primary and secondary carbonate cements.

The spatial arrangement of the mineralogical components, except heavy minerals, is well-organized and shows a trend corresponding to the direction of shortening recorded in the compaction bands. The trend is highlighted especially in the case of micas, which are oriented under moderate to high angles with respect to the shortening direction. The observed deformational fabric is a result of plastic deformation in poorly indurated sediments. As demonstrated, our workflow can facilitate the interpretation of rock deformation mechanism at the micro-scale. This methodological approach can be applied to any other rock type.

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AMS as a tool for interpretation of shear zones: analogue modelling

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The Anisotropy of magnetic susceptibility (AMS) as a dimensionless material parameter describes the degree of magnetization of a material in response to an applied magnetic field in different directions. AMS measurements reflect a summed magnetic signal of shape preferred and crystallographic orientation of all rock forming mineral grains. Therefore the AMS has become a widely used technique in structural geology as useful, precise and quick method to quantify the internal rock fabric. However, the lack of comprehensive knowledge about the governing processes of AMS in rocks can make the AMS interpretation difficult. There is a broad discussion related to origin of the magnetic fabric, its relationship with the bulk deformation and strain memory of rock. The analogue modelling of magnetic fabric in shear-zones was used to explore the time and space relationships between the finite strain and AMS by providing new experimental data.

Previously, a relationship of AMS with increasing strain has been studied experimentally in plasticine, deformed sandstones, magnetite bearing sand bonded with cement and during preparation and compaction of calcite and muscovite aggregate and simple shear experiments on mixture of silicone and wax. A large shear-box was designed to enable different strain rates and also shear-zone of variable width. The experiments were produced with the coloured plaster of Paris with homogeneously admixed fine-grained magnetite and powder retarding the solidification reaction. The used analogue material displays a peculiar strain-rate dependent rheology (thixotropy) and is capable to well-reproduce the strain localization up to brittle failure and very well corresponds to natural rocks. Experimentally produced magnetic fabric related to simple shear deformation in plaster is analysed in terms of the AMS.

By varying experimental strain rate we were able to model not only ductile to brittle behaviour of the shear-zones, but also observe the AMS evolution with the strain localization. Correlation is observed between the strain rate and the width of the shear-zone identified from the reoriented magnetic fabric. Very interesting is development of the AMS shape parameter T from the edge of the shear-zone to its core. AMS ellipsoid changes from background primary fabric to more prolate shapes in shear-zone margins and then back to neutral shapes in core of shear-zone. This gradual development is probably connected with the evolution of the constriction fabric and/or transposition and the subsequent destruction of the primary magnetic fabric in the middle of the shear-zone. Our experiments suggest that AMS-strain relationship is not straightforward and proper interpretation of AMS fabric from shear-zones requires additional analyses to by correctly interpreted.

Deformation localization reflected by the anisotropy of magnetic susceptibility: natural shear zone in calcite

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We provide the relationship between the Anisotropy of magnetic susceptibility (AMS) and strain in a marble shear zone by combining rock magnetic studies, detailed microstructural analysis and CPO-based numerical modelling of the AMS. The AMS is regularly applied as a tool to infer structural analysis of deformation and flow in rocks. The AMS record reflect an integrated magnetic signal of crystallographic and shape preferred orientation of all mineral grains forming the rock. The microstructure of a rock is often a complex combination of distinct microstructural features of diverse origins, orientations and strengths. Therefore, it is important to evaluate the contributions of the main susceptibility carriers to the anisotropy as well as identify the processes responsible for the AMS development and eventual superpositions of corresponding microstructures. To interpret strain-AMS relationship, we have implemented microstructural analysis and numerical modelling constructed based on microstructure, CPO, modal and chemical composition of constituting minerals. The AMS results exhibit oblique fabrics at high-angle with respect to primary fabric and gradually being rotated towards the SZ plane with increasing strain. The documented AMS fabric is “inverse” as the calcite c-axes are consistent with the k1 orientation proving this inverse AMS fabrics. The AMS shows also an angular deviation from the local macroscopic fabric observed in the shear zone, systematically increasing with the increasing strain. The microstructural evolution related to the shear zone development is characterized by dynamic recrystallization of a primary coarse-grained calcite microstructure. The increasing strain is accommodated by increasing amount of recrystallized matrix at the porphyroclasts expense. The numerical modeling proved that the recorded AMS is controlled by calcite and dolomite crystallographic preferred orientations and the “inverse” character is caused by high Fe concentration in dolomite. The angular deviation of AMS is a result of the presence of microstructural subfabrics of coarse porphyroclasts and fine-grained recrystallized matrix produced by localization. We concluded that the localization of deformation should be considered whenever interpreting AMS in deformed rocks and regions and that the AMS studies should be accompanied by microstructural analyses.

Dilation and compaction accompanying changes in slip-velocity in clay-bearing fault gouges

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Many natural fault cores comprise volumes of extremely fine, low permeability, clay-bearing fault rocks. Should these fault rocks undergo transient volume changes in response to changes in fault slip velocity, the subsequent pore pressure transients would produce significant fault weakening or strengthening, strongly affecting earthquake nucleation and possibly leading to episodic slow slip events. Dilatancy at slow slip velocity has previously been measured in quartz-rich gouges but little is known about gouge containing clay. In this work, the mechanical behaviour of synthetic quartz-kaolinite fault gouges and their response to velocity step changes were investigated in a suite of triaxial deformation experiments at effective pressures of 60MPa, 25MPa and 10MPa. Clay content was varied from 0 to 100% and slip velocity was varied between 0.3 and 3 microns/s.

Upon a 10-fold velocity increase or decrease, gouges of all kaolinite-quartz contents displayed measurable volume change transients. The results show the volume change transients are independent of effective pressure but dependent on gouge composition. As kaolinite content increased, the magnitude of the transient pore volume change decreased slightly. At 25MPa effective pressure, the normalised volume changes decreased from 0.1% to 0.06% at 10% to 100% kaolinite.

Low permeabilities of clay-rich fault gouges, coupled with the observed volume change transients, could produce pore pressure fluctuations up to 10MPa in response to fault slip. This assumes no fluid escape from an isolated fault core. Where the permeability is finite, any pore pressure changes will mediated by fluid influx into the gouge, thus producing a stronger response in low permeability gouge. Volume change transients could therefore be a significant factor in determining whether fault slip leads to earthquake nucleation or a dampened response, possibly resulting in episodic slow slip in low permeability fault rock volumes.

Fluid chemistry and earthquake rupture - Investigation of co-seismic chemical reactions: an experimental approach

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When fluid-rock interactions occur in an active fault-zone, they can influence fault failure mechanics by altering chemical and physical properties of the damage zone and fault core. Reactions driven by aqueous fluids may modulate the earthquake cycle by changing the nature of fault rupture through altering material properties by precipatating weak secondary minerals, sealing fault zones, and facilitating the generation of high pore fluid pressure. Past work has focused on aqueous fluids restrengthening and altering material properties, pressure cycling during earthquake nucleation and heat redistribution through crustal fluid flow. However, details of fluid-rock reactions occuring at different times in the seismic cycle, particularly co-seismicly, remain unconstrained. What is the effect of co-seismic chemical reactions on fault behaviour? Can changes in regional fluid chemistry reveal fault activity at depth? A combined geomechanical and geochemical experimental approach will shed light on these questions, but initally we define the missing links between these two approaches.

Fault gouges (both synthetic and natural) will be experimentally faulted in contact with a hydrothermal fluid to interrogate co-seismic chemical reactions. Fluid and rock samples will be geochemically and isotopically characterised prior to, and after experimental work to identify mineralogical and chemical changes that occur during simulated earthquake slip under different conditions. The reactions driving these changes will then be related to variability measured in the fluid permeability, mechanical and frictional properties of the investigated materials to identify the chemical reactions that occur and their control on fault gouge physical properties and earthquake rupture. This study, coupling geochemical analyses of fluids and rocks during simulated earthquake slip, will be the first of its kind to fully interrogate coseismic chemical reactions.

Strain and strain-rate dependent rheology of antigorite at mantle wedge conditions – geological evidence.

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Antigorite serpentine is stable in hydrated ultramafic rocks at temperatures between 300-600 °C at 1-4 GPa, and is thought to be especially common along subduction zones, where fluid released from subducting oceanic lithosphere hydrates the overlying mantle wedge. The inferred low viscosity of antigorite at mantle-wedge conditions suggests that it may strongly influence slab-mantle coupling. However, the rheology of antigorite is poorly constrained. Deformation experiments have produced contradictory results; some studies suggest a dislocation creep mechanism, while others suggest frictional deformation. Geological investigations of antigorite deformed naturally in a mantle-wedge setting are needed to better constrain the rheology of antigorite.

The Cretaceous Nishisonogi Metamorphic Rocks (NMR) exposed near Nagasaki, SW Japan, contains lenses of antigorite serpentine within a matrix of epidote-blueschist facies amphibolite. Kinematic indicators within the NMR imply non-coaxial shear with top-south kinematics, consistent with the kinematics inferred for Cretaceous subduction along the eastern Eurasian margin. Antigorite serpentine in the NMR shows two end-member fabrics: (a) an isometric, interpenetrating fabric, and (b), a foliated fabric. Interpenetrating antigorite occurs in lenses within relatively well-foliated antigorite. Transition between interpenetrating and foliated fabric types is accompanied by a substantial reduction in grain size, and rotation of grain long-axes towards the foliation. Tensile and hybrid tensile-shear veins cut the antigorite foliation, but the veins are also offset along foliation planes, implying cyclicity between ductile and brittle deformation.

The above observations demonstrate that fabric development in antigorite is assisted by progressive non-coaxial strain, and is accompanied by strain localisation likely reflecting a reduction in strength. Grain size reduction during fabric development suggests a component of frictional deformation. Strain incompatibilities arising during the development of a preferred orientation might be resolved by dissolution-precipitation. In foliated antigorite, the strong alignment of cleavage suggests slip along cleavage planes. Cyclicity between brittle and ductile deformation indicates the NMR serpentinite experienced variable effective stresses and/or strain rates, and implies a stress and/or strain-rate dependent rheology. More generally, that antigorite occurs as lenses within amphibolite implies that antigorite is more viscous than amphibolite, challenging models that invoke a weak serpentine layer lubricating plate interface slip.

The frictional-viscous transition in calcite: how grain-scale heterogeneities control natural deformation

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In the upper crust calcite typically deforms by fluid-assisted mass transfer at lower stresses and cataclasis at higher stresses. Calcite solubility decreases with increasing temperature, and becomes too low for mass transfer to be relevant within natural shear zones at around 150°C. At higher temperatures (>350°C), strain rates from both grain-size-sensitive and -insensitive creep are potentially sufficient to accommodate deformation at geologically-relevant strain rates. Between 150°C and 350°C, laboratory experiments suggest frictional deformation is preferred over viscous mechanisms in calcite. Despite this, natural examples of crystal-plastic deformation microstructures have been recorded within a strike slip fault deformed at temperatures <150°C (Bauer et al., *Geology*, 2018). To highlight how composition and secondary phases affect the deformation of natural calcite aggregates at 150˚C < T < 350˚C, we present microstructural data collected from two calcite veins deformed at 260±10°C during Devonian subduction of the Gwna Complex at Llanddwyn Island, Anglesey, UK.

The first example is a reactivated calcite vein within a limestone clast in a phyllosilicate-dominated mélange. The vein has been ductilely sheared to a shear strain of ~5 and comprises fine-grained recrystallised calcite between elongate coarser grains. The vein microstructure indicates that dislocation creep of coarser relict calcite led to subgrain rotation, grain-size reduction, and grain-size-sensitive creep of recrystallised grains. The ductilely deformed vein has Mg content 2-3 wt% lower than the adjacent, undeformed, calcite.

The second example is a series of veins, subparallel to foliation, in a mélange derived from altered volcaniclastics. The veins contain fine-grained (<10 µm) recrystallised calcite and are commonly deformed to shear strains of 4-5, locally as high as 10. Secondary phases (quartz, albite, chlorite) are scattered throughout the veins, commonly smeared along horizons subparallel to the slip direction where they pin calcite grain boundaries and maintain fine grain sizes. Calcite grains form a weak S-C fabric, consistent with deformation within fine-grained horizons rich in secondary phases.

These examples highlight how locally-variable chemistry and secondary phases can localise deformation by limiting dislocation creep or pinning grain boundaries, intensifying strain-dependent effects within these volumes. Variable chemistry and secondary phases are likely near-ubiquitous within natural calcite-rich rocks, suggesting these inherent heterogeneities may commonly localise deformation in the lithosphere and permit viscous deformation within a typically frictional temperature range.

The role of the fracture surface in the formation of vein microstructures

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Mineral veins in nature show a diversity of microstructures, ranging from blocky, to fibrous and stretched crystal morphologies. These microstructures can be used to gain insights into the conditions of vein formation. For example, blocky veins are considered to form in open fractures, whereas fibrous morphologies suggest crystal growth rates that are comparable to the fracture opening rates. However, the blockyness or fibrosity of the veins also depend on the crystal habits. Furthermore, the shape orientation of vein crystals can reveal the fracture opening trajectory and shear component, but it is reliable only if the fracture wall has a certain roughness. Over the recent years, numerical modelling has provided significant insights on how different factors and interplay between them control vein formation. However, despite the fact that in many veins crystal growth proceeds by epitaxial precipitation on host rock grains, the role of the compositional and structural characteristics of the fracture surface has been rarely discussed.

This contribution will present results from studies combining phase-field modelling approach with analysis of natural vein microstructures and experiments, focused on investigating vein formation in a wide range of carbonate host rocks. We show that different fracture surface characteristics (proportion of transgranular vs intergranular fracture segments, accessory minerals and grain size distribution) that result from the diversity of carbonate microstructures, play a significant role on the crystal growth in veins. These parameters are systematically explored in 2D models and classified in microstructure maps.

Our results can be easily extended to include multiple crack-seal events and degrees of pore cementation, providing a generic platform for modeling structural diagenesis in limestones.

A previously undescribed type of synkinematic porosity forming in the strain shadows of rotating porphyroclasts in ultramylonites

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At the brittle-to-ductile transition, shear zones are important conduits that facilitate the migration of fluids and dissolved solids across the transition from upper crustal hydrostatic to lower crustal lithostatic pore fluid pressure regimes. It is a relatively recent revelation that the deformation in shear zones can result in the development of synkinematic pores and dynamic permeable networks. These synkinematic porous microstructures influence a shear zone's hydraulic transport properties, facilitating fluid-rock interactions and mass transfer in general. Details of this porous microstructure, and its integration with the kinematics and dynamics of shear zones are still poorly understood. Here we show a previously undescribed form of synkinematic porosity in an unweathered psammitic ultramylonite from the Cap de Creus Northern Shear Belt (Spain). The sizeable, open pores appear exclusively next to albitic feldspar porphyroclasts, which themselves float in a fine-grained, polymineralic ultramylonitic matrix. The pores wrap around their host clasts, occupying strain shadows. A detailed analysis using high-resolution backscatter electron imaging and synchrotron-based x-ray microtomography confirms that the pores are isolated from each other. Our study found no evidence for weathering of the samples, or any significant post-mylonitic overprint. Our microstructural observations suggest that the pores formed synkinematically as a result of a tensile decoupling between the feldspar clasts and their surrounding ultramylonitic matrix. In our model, we envisage this decoupling to be enabled by the rotations of the porphyroclasts in the ultramylonitic matrix that deforms predominantly by viscous grain boundary sliding, and where particles move essentially all parallel to the shear direction. We infer that the tensile decoupling established a hydraulic gradient that drained the matrix and filled the pores with fluid. The fact that the pores remain open suggests a chemical equilibrium with the fluid. This form of synkinematic porosity constitutes a puzzling, yet obvious way to maintain surprisingly large fluid reservoirs in ultramylonites whose transport properties are otherwise likely determined by creep cavitation and the granular fluid pump. Our findings add another puzzle piece to our evolving understanding of synkinematic transport properties of mid-crustal ultramylonites and fluid-rock interaction in shear zones at the brittle-to-ductile transition.

EBSD-based criteria for the identification of the former presence of coesite: application to a metagranite from the Tso Morari dome, Himalaya

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Ultrahigh-pressure (UHP) metamorphism observed in continental terranes implies that continental crust can subduct to ~40 kbar before exhuming to the surface. This process is one of the least understood and widely debated parts of the orogenic cycle. The dominantly felsic composition of UHP continental terranes means that petrology-based techniques for determining peak pressures and temperatures are often not possible. In such cases, the detection of UHP conditions depends on the preservation of coesite, a rarely preserved mineral in exhumed UHP terranes as it rapidly transforms to quartz on decompression[1]. In the absence of coesite, evidence for subduction to UHP is entirely dependent on the qualitative identification of 'palisade' quartz microstructures, which are thought to form after coesite[2].

In this study, we compare the results of EBSD and misorientation analysis of palisade quartz in two samples. The first is a sample of pyrope quartzite from the Dora Maira massif in the Alps, which contains palisade quartz, surrounding a relict coesite inclusion in garnet. The second is a sample of low-strain Polokongka La granite from the Tso Morari complex in the Ladakh Himalaya, which contains matrix-scale palisade quartz. These unrelated occurrences of palisade quartz preserve crystallographic relationships common to both samples, strongly supporting our interpretation that the following features can be used as a systematic and predictable set of criteria to identify the former presence of coesite: (1) Quartz crystallographic orientations define spatially and texturally distinct subdomains of palisade quartz grains with 'single crystal' orientations defined by distinct c-axis point-maxima. (2) Adjacent subdomains are misorientated with respect to each other by a misorientation angle/axis of 90°/<a>. (3) Within each subdomain, palisade quartz grain boundaries commonly have intra- and inter-granular misorientations of 60°/[0001], consistent with the dauphiné-twin law.

Our observations imply that the coesite-to-quartz transformation is crystallographically controlled by the epitaxial nucleation of palisade quartz on the former coesite grain, specifically on potential coesite twin planes such as ($\bar{1}01$) and (021). In the absence of coesite, our EBSD-based observations may represent the only quantitative indicator of UHP conditions in low-strain enclaves of felsic and siliceous rocks of continental terranes.

1. Bohlen, S. R. & Boettcher, A. L. The quartz ⇆ coesite transformation: A precise determination and the effects of other components. *J. Geophys. Res. Solid Earth* **87**, 7073–7078 (1982).
2. Schertl, H.-P., Schreyer, W. & Chopin, C. The pyrope-coesite rocks and their country rocks at Parigi, Dora Maira Massif, Western Alps: detailed petrography, mineral chemistry and PT-path. *Contrib. to Mineral. Petrol.* **108**, 1–21 (1991).

Analysing crystal distortions to deduce dislocation slip systems

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In many parts of the Earth rocks deform by dislocation creep. There is therefore a need to understand which slip systems operated in nature and in experimental products. Knowing the conditions of experiments may then allow natural conditions and strain rates to be characterised. Dislocation creep typically gives lattice preferred orientations (LPOs), since activity on particular slip systems leads to lattice rotations and alignment. For decades LPOs, measured first optically and since the 1990s by EBSD, have been used to infer slip systems. This is a valuable technique but the link between slip sytem activity and LPO is complicated, especially if recrystallisation and/or grain boundary sliding have been involved.

Here we present a more direct method to deduce “geometrically necessary” dislocations (GNDs) from the distortions within crystals. Distortions may be optically visible (e.g. undulose extinction in quartz) but EBSD has revealed how common distortions are, and allowed them to be quantified. The method does not give the complete picture of GNDs but allows hypotheses to be tested about possible slip systems. We illustrate this “Weighted Burgers Vector” method with a number of examples. In olivine the method distinguishes slip parallel to a and c, and in plastically deformed plagioclase it reveals a variety of slip systems which would be difficuilt to deduce from LPOs alone. GNDs may not necessarily reflect the full slip system activity, since many dislocations will have passed through crystals and merged with grain boundaries leaving no signature. Neverthless the method highlights what dislocations are present “stranded” in the microstructure. In many case these will have been produced by deformation although the method can also characterise growth defects.

A comparison of different methods for estimating penetrative strain using natural and synthetic data: A study from the Sikkim Himalaya

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Convergence-related shortening gets partitioned across scales and spatially during mountain building processes. For example, in the Himalayan fold thrust belt (FTB), ~477-919 km minimum shortening is estimated from a series of folded, south vergent thrust systems that vary laterally in their geometry resulting in laterally varying shortening distribution. From hinterland to foreland, these major faults are the Main Central thrust, the Pellng-Munsiari thrust, the Lesser Himalayan duplex, the Main Boundary thrust, and the Main Frontal thrust; they are bounded in the north by the the South Tibetan Detachment system. However, these shortening estimates do not include contribution from the penetrative strain fabrics that can accommodate a significant amount of the FTB shortening. To estimate the contribution from the penetrative strain, we analyzed 201 thin-sections cut from 96 quartz-rich samples (sandstone, quartzite, phyllite, schist, and gneiss) across these major thrust sheets from the Sikkim Himalayan FTB that lies in the eastern Himalaya. Here, the structural geometry laterally varies over ~15 km lateral distance. Based on two regional, transport-parallel balanced cross-sections, ~542 km and ~589 km of total minimum shortening have been estimated from eastern and western Sikkim, respectively.

Penetrative strain results indicate that strain magnitude (R_S) remains higher in the internal thrust sheets (~1.4-2.43), and it progressively decreases in the frontal thrust sheets (~1.08-1.51). The normalized Fry and the R_f-φ are the two most commonly used graphical methods to estimate best-fit strain ellipse parameters, i.e., R_S and φ (long-axis orientation). However, in low-magnitude frontal thrust sheets, where initial grain shapes were not spherical, these graphical methods do not accurately estimate the best-fit strain ellipse parameters. In this study, we compare the accuracy of these strain methods as a function of lithology, texture, and structural position within the orogenic wedge. The central vacancy in the Fry plot was objectively fitted using the enhanced Fry (EFRY), the point-count density (PCD), the continuous function method (CFM), and weighted least square (WLS) methods. From the R_f-φ data, we calculated the best-fit strain ellipse using the shape matric eigenvector (SME) method. In the internal thrust sheets, the SME method accurately estimates penetrative strain. The WLS method records the lowest bootstrap error in the frontal thrust sheets, followed by the SME method. We also created multiple synthetic aggregates containing 110 random elliptical grains with random long-axis orientations. We deformed these aggregates under pure-shear, simple-shear, and general-shear conditions at 30 different deformation increments. For every strain method and every deformation condition, we calculated the Root Mean Square Error (RMSE) to understand the accuracy of these strain methods in estimating the penetrative strain. Preliminary results using the synthetic aggregates indicate that overall the SME method provides a better estimate of the strain parameters. However, the WLS method more accurately estimates long-axis orientations. Therefore, this study shows that the SME method overall yields a better strain estimate.

Foliation Boudinage Structures at the Mount Isa Cu-Pb-Zn System

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Over the last 50 years, foliation boudinage structures have been well documented within homogeneous, anisotropic rocks. Structures with similar or identical geometries to foliation boudinage structures have also been documented during this time, including internal boudinage and flanking folds. The use of different names for structures with such similar geometries has given rise to some confusion since their early definitions. A review of foliation boudinage structures, internal boudinage and flanking folds clarifies that one of the diagnostic features of foliation boudinage structures is the occurrence of a fracture and loss of continuity. A comprehensive survey of the *PT* conditions during the development of foliation boudinage structures shows that by far the majority have formed at greenschist and amphibolite facies, perhaps reflecting that fracture at higher metamorphic grades requires unusual conditions.

Two approaches to visualising the geometry of drill core scale foliation boudinage structures in 3-dimensions have been taken; CT scanning and 3-dimensional modelling using serial sections. A series of polished sections made through a foliation boudinage structure are used with the MOVE software suite to construct the model. The serial section approach has the advantage that mineralogy can be directly identified and modelled from polished sections.

Underground mapping and drill core logging has identified that foliation boudinage structures are common at the drill core scale in the Mount Isa Cu-Pb-Zn system. Foliation boudinage structures are observed principally in the shale lithologies, with the foliation boudinage neck lineations plunging gently and always lying on or close to the plane of the bedding. This geometry is compatible with their formation in the regional D2 deformation event. Fracturing associated with foliation boudinage may have played a key role in facilitating fluid flow and alteration prior to the main mineralising event.

Dynamics and rheologies of finite deformation in Yaounde and its environs (Cameroon) meta-volcano-sediments, Neoproterozoic and Post-Neoproterozoic

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The present study is a contribution to the knowledge of the geology of Yaounde and its environs by providing new structural data; taking into account the problem of acquiring geochronological data for relative dating in a polycyclic context. It relied on the analysis of structural elements to develop a reflection on the regional meanings of mesoscopic increments of deformation and to propose models of dynamics and rheology of the finite deformation. It has thus made it possible to highlight five deformation phases, including four ductile pan-African (D1-D4) and one late-pan-African to post-pan-African brittle (D5). The ductile deformation phase D1, which can be observed along the cutting fronts by foliation S1, was a simple shear with direction E-W to NE-SW; it was supplanted by another ductile phase D2, which has foliation S2 and a bi-directional stretching boudinage B2 N-S to SSW-NNE and E-W to WNW-ESE, and structures with preferential stretching N-S to SW-NE. There are also F2 folds whose axial planes are parallel to the L2 linearization of direction N-S to SW-NE. The two subsequent phases are ductile and transpressive D3 and D4. They set up the megascopic folds P3 and P4, resulting in megascopic bends B3 and B4 (fig. 1a). The continuum of the transpressive regime in the brittle domain (D5) set up fractures in the Riedel system in a shear band oriented N090E to N070E. This system shows retroverted R and R' fractures and proverses P and P'. The retroverted fractures have N088E to N090E and N160E average orientations, respectively, while the proverses fractures have N040E to N058E and N000E average orientations, respectively (fig. 1b).

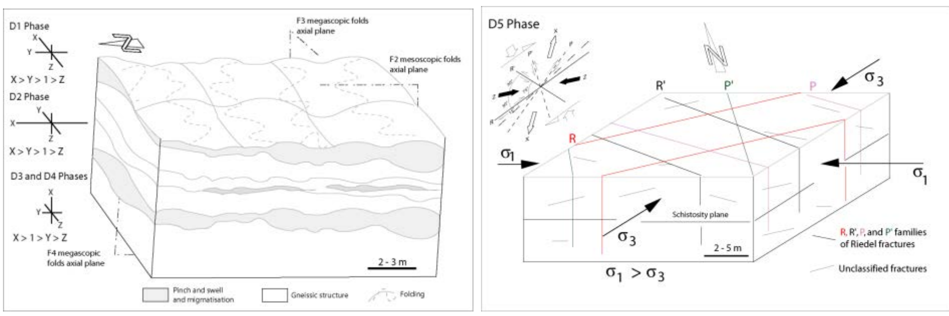

Figure 1 : Dynamics and rhéologies of finite deformation in Yaounde and its environs meta-volcano-sediments. (a) Ductile and (b) fragile deformations.

Keywords: Boudinage, Rheology, Riedel system, Shear, Deformation, Yaounde.

A thermomechanical modeling for the Sergipano fold belt: comparative analysis

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The Sergipano fold belt is a Neoproterozoic terrain, located in northeastern Brazil. This fold belt is a collisional orogen that was generated from the collision between Congo-São Francisco Craton and Pernambuco-Alagoas (PEAL) Massif. This work presents a comparative analysis field data with a thermomechanical modeling, in order to verify the computational method effectiveness and understand collision mechanics forming the orogen that gave rise to the fold belt (Figure).

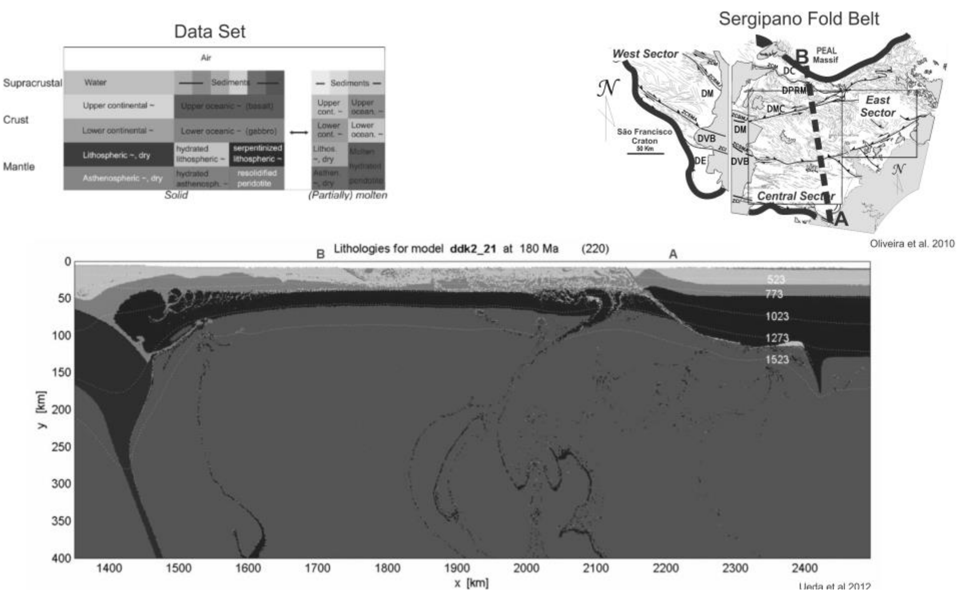

Figura 1: Comparative analysis of collisional modeling (inner) for the Sergipano Fold Belt (right, upper).

We compared numerical simulation data with field and petrographic data, thereby we got a crust behavior during the formation of a collisional orogen. From the simulations obtained, we were able to characterize the geological domains of Sergipano fold belt, as well as associate the degrees of metamorphism and the lithological types observed in the field.

This methodolgy managed to propose new models for the origin of certain lithologies in the fold belt (structural relationship of granite placement, origin of some mafic bodies, and distribution of metasedimentary country rocks), and that did not have their formation well defined in the literature. The geochemical data compiled, also validated the computer simulation as a good analogue for the evolution of the Sergipano fold belt, because the temperature and pressure ranges obtained were in agreement with the data in the literature. It was also possible to verify the influence of the crustal delamination in the formation of igneous bodies in the region.

Complex kinematics in a major ductile shear zone, NW Shetland: Evidence of ductile extrusion during Caledonian transpression?

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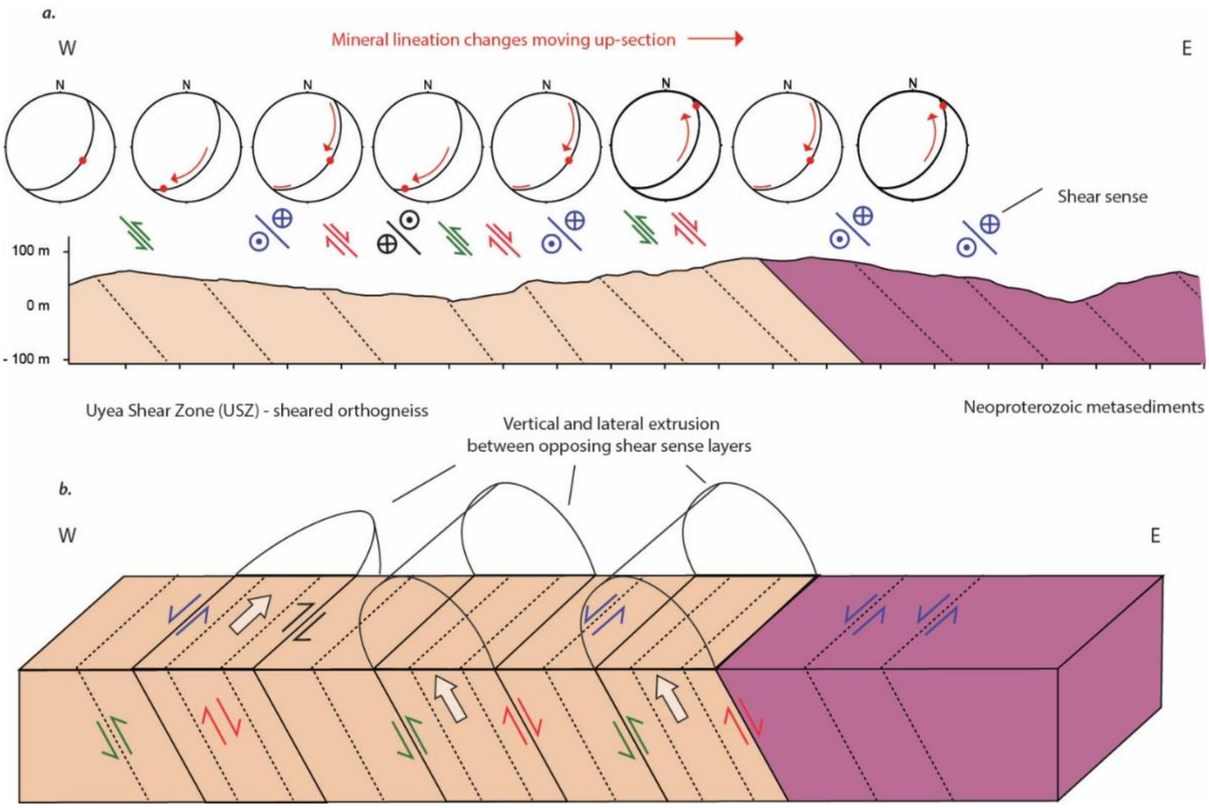
Ductile shear zones are heterogeneous areas of strain localisation which often display variation in strain geometry and combinations of coaxial and non-coaxial deformation. One such heterogeneous shear zone is the *c.* 2 km thick Uyea Shear Zone (USZ) in northwest Mainland Shetland (UK), which separates variably deformed Neoarchaean orthogneisses in its footwall from 'Moine' Neoproterozoic metasediments in its hanging wall (Fig. a). The USZ is characterised by decimetre-scale layers of dip-slip thrusting and extension, strike-slip sinistral and dextral shear senses and interleaved ultramylonitic coaxially deformed horizons. Within the zones of transition between shear sense layers, mineral lineations swing from foliation down-dip to foliation-parallel in kinematically compatible, anticlockwise/clockwise-rotations on a local and regional scale (Fig. b). Rb-Sr dating of white mica grains via laser ablation indicates a *c.* 440-425 Ma Caledonian age for dip-slip and strike-slip layers and an 800 Ma Neoproterozoic age for coaxial layers. We propose that a Neoproterozoic, coaxial event is overprinted by Caledonian sinistral transpression under upper greenschist/lower amphibolite facies conditions. Interleaved kinematics and mineral lineation swings are attributed to result from differential flow rates resulting in vertical and lateral extrusion and indicate regional-scale sinistral transpression during the Caledonian orogeny in NW Shetland. This study highlights the importance of linking geochronology to microstructures in a poly-deformed terrane and is a rare example of a highly heterogeneous shear zone in which both vertical and lateral extrusion occurred during transpression.



Near Orthogonal Interference Fold Patterns and Geotectonic Meaning of Icaiçara Terrane as part of Accrettion Tectonics in Brazilian-Pan-African Orogeny in Western Gondwana

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The Icaiçara Domain (TIC) constitutes a crustal segment interpreted as a *basement inlier* or exotic terrane. It is located on the westernmost portion of the Piancó-Alto Brígida Belt within the Borborema Province. Their lithological associations are grouped in the Barro (schists, paragneiss, quartzites, marbles and calc-silicate rocks) and Parnamirim (ortho- and paragneiss finely banded to mylonitic, with incipient migmatization) complexes. In addition there are intrusions of granitic-granodioritic *augen*-gneisses. The structural framework of this terrane comprises an overturned antiform mega-fold with an axial surface (S_{ax3}) which formed in response to the strong shortening imposed by the Brasiliano cycle. In the central part of the TIC, low-angle foliation planes (0-30º) and high-pitch (rake) mineral stretching lineations are preserved, being sistematically folded towards the terrane margin. Geometric analysis of foliation and lineation allowed us to infer that the general structure of this inlier corresponds to an interference fold pattern of the "egg-box" or "domes and basins" type, in which the past axial surfaces (S_{ax1}) with axis L_{b1} with E-W direction were found overturned by orthogonal surfaces (S_{ax2}), mainly affecting rocks of the Barro Complex, since Lb and Lx become parallel to each one. The past deformational markers are still affected by tectonics, especially in the southern portion, where mylonites predominate connected to the Pernambuco Lineament, imposing a strong crustal stretch along the E-W direction. The TIC is still deformed to the east by the Parnamirim-Riacho dos Bezerros Shear Zone, and to the west by the Trempe Shear Zone, both with NE-SW direction and sinistral-flow kinematics. These structures can correspond either to the accommodation of the transport of this crustal block through lateral escape mechanisms or even through the reactivation of deep suture zones, involving the obduction of oceanic crust, since retroeclogitic rocks of the Mafic-Ultramafic Suit called Fazenda Esperança occur closer to these shear zones. Additional geochronological, structural and petrogenetic data are needed to understand how the TIC evolved within the context of the Piancó-Alto Brígida Belt, since these folding interference patterns can be monophasic (progressive in the same event) or polyphasic (each folding phase would be related to a distinct orogenic event). The Icaiçara Fragment thus constitutes an important crustal segment for understanding the lithospheric evolution of the Borborema Province in the accretion tectonics model of Brasilian-Pan-African Orogeny.

Cenozoic relative movements of Greenland and North America by closure of the North Atlantic – Arctic plate circuit

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Models of Cenozoic plate motions between Greenland and North America often use magnetic anomalies in the Labrador Sea and Baffin Bay regions. The crustal origin of some of the older magnetic signatures, (pre C24, Paleocene) is questioned, and these models often portray Paleogene motions inconsistent with geological data from Nares Strait region. We test for a connection motions inconsistent with geological data from Nares Strait region. We test for a connection between the (mis)interpretation of anomalies and inconsistencies between model predictions and geological evidence by constructing a regional model that is not based on magnetic data in the Labrador Sea region. We do this by closing the North America – Greenland – Eurasian plate circuit from the Paleocene to Eocene – Oligocene Boundary (C25 – C13). Our findings show seafloor spreading in the Labrador Sea initiated during Eocene, and not Paleocene, times. In turn, we argue that C24 and older isochrons in the Labrador Sea are not suitable as isochron markers for modelling plate motions. We further show that the previously noted counterclockwise rotation of Greenland, marking the beginning of plate convergence in the eastern Canadian Arctic, is not a result of changes in seafloor spreading direction, but instead of the initiation of seafloor spreading in the Labrador Sea. Our model shows ~160km of shortening in the Eastern Canadian Arctic.

Incision migration across Eastern Tibet controlled by monsoonal climate, not tectonics

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The formation and uplift history of the Tibetan Plateau, driven by the India-Eurasia collision, is the subject of intense research. We analyse the link between climate and tectonics in the central and eastern Tibetan Plateau using geomorphic indices of surface roughness (SR) hypsometric integral (HI) and elevation-relief ratio (ZR) and mean annual precipitation, thermochronology and erosion rate data. Geomorphic indices capture the landscape response to competition between climate and tectonics and reflect the spatial distribution of erosion. Competing tectonic models in the region suggest either early Cenozoic plateau growth, or a late phase of crustal thickening, surface uplift and plateau growth driven by lower crustal flow ("channel flow"). Swath profiles of rainfall, elevation and the geomorphic indices were constructed, orthogonal to the internal drainage boundary and segmented linear regression was used to identify trend changes. We identify a broad ˜WSW-ENE trending transition in the landscape where changes in landscape and precipitation are grouped and in alignment. It represents, from east to west, a sharp decline in precipitation (interpreted as the western extent the East Asian Summer Monsoon), a change to a low relief landscape at 4500-5000 m elevation, an increase in ZR and a transition to low HI and SR. This zone cuts across structural boundaries and is not a drainage divide: the main rivers have their headwaters further West, in the interior of the plateau. We argue that this geomorphic-climatic transition zone represents a change from incised to non-incised landscapes, the location of which is controlled by the western extent of summer monsoon precipitation. Compiled thermochronology data shows an increase in exhumation from ˜25 Ma in the incised area but no evidence of this increased exhumation in the non-incised area. This pattern supports a model of early Cenozoic growth of the eastern Tibetan Plateau, superimposed by incision driven by monsoon intensification. Modern erosion rates are lower in the non-incised region, west of the monsoon extent (mean 0.02 mm/yr), than the incised region (mean 0.26 mm/yr). These rates appear high enough to form the modern day landscape following Miocene monsoon intensification. Our results do not support the channel flow model, which would predict an eastwards wave of surface uplift and therefore erosion and exhumation during the Miocene, which are not present in the data.

East Asian orogenic collapse caused by oblique subduction and reduced boundary force

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East Asia experienced compressional and then extensional deformation in the Mesozoic, across the South China Block, North China Craton (NCC) and the part of the Central Asian Orogenic Belt to the north of the NCC. Deformation and magmatism resulted from Triassic collisions that accreted the continental blocks, and also Izanagi (Paleo-Pacific) Plate subduction from the east. The causes and timings of these processes are highly debated, especially loss of the lower lithosphere of the NCC. Here, we synthesize evidence for late Mesozoic and early Cenozoic crustal thinning via extension and denudation, to quantify the previous crustal thickness. We find that there was a ~50 km thick crust by the Middle Jurassic across much of the area between NE Asia and SW China, which has since undergone ~30% thinning. A force balance indicates that the buoyancy force produced by the gravitational potential energy of this thick crust drove extension from the latest Jurassic - Early Cretaceous (~145 Ma), when a rapid switch from orthogonal to oblique subduction at the Asia-Izanagi plate margin reduced the compressive boundary force by ~30%. Mantle lithosphere thinning of the NCC exceeds crustal thinning by a factor of ~2; extensional collapse cannot be the only cause of cratonic destruction, but played a major role, and potentially triggered mantle instability.

Possible tearing and faulting mechanism in the lower crust of the Indian Plate: Insights from the Moment tensor inversions of the earthquakes from Garhwal Himalaya.

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Majority of the earthqukes in the Himalayan collision zone are compressional in nature and occurring around the mid crustal ramp of the detachment (aka Main Himalayan Thrust), which is located in the upper crust. These upper crustal earthquakes have been studied exclusively and reported in various studies. However, the lower crustal earthquakes and (or) upper mantle earthqukes of the Himalaya and it's faulting mechanisms have not been studied extensively. In this study we have studied the kinematics and faulting mechanisms of lower crustal earthquakes in the Garhwal Himalaya, which is located in the central seismic gap, using Moment Tensor InveInversion

The distinct presence of both the Pg and Pn phases from these earthquakes shows that the seismic stations have received both the direct crustal phases as well as the Moho reflected phases suggesting the lower crustal origin for these earthquakes. The Moment Tensor solutions reveal that the lower crust show predominantly strike-slip faulting mechanism and most of them are located around the Moho along the lithospheric flexure of the Indian plate; in contrast to the thrust dominant upper crust. The principle compressive horizontal stress is orientated parallel to the relative motion of the Indian plate, which is the driving force in the lower crust as similar to the upper crust of the region. However, the lower crust show oblique stress orientation, suggesting the influence of bending plate forces and mountain load in generating these earthquakes. We compared this scenerio with other regions of the Central Himalaya viz., kumaun, Nepal and Sikkim and attribute the results (strike slip faulting) as the tearing of the lower crust of the Indian plate. Furthermore, we suggest that the lower crust cannot be ruled out from having potential to generate major earthquake(s) in the future.

Structural style of the frontal fold-and-thrust belt and syntectonic mineral vein evolution at the Chachas area in the Western Cordillera (Central Peruvian Andes)

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The Andes, with their abundance of vast and complete outcrops, make a perfect tectonic laboratory. However, the researchers so far focused mainly on tectonic analysis on continental and regional scales; time-consuming and labor-intensive mesotectonic field measurements are not commonly found in the literature. In this study, we aimed to reconstruct the structural evolution of the Mesozoic strata in the Frontal Fold and Thrust Belt of the Western Cordillera in southern Peru, based on field observations and measurements, detailed structural analysis, and microscopic vein analysis.

The applied approach enabled us to identify several stages of intense tectonic deformation related to bivergent thrusting in the Western Cordillera with accompanying structures that could be produced by the NE-SW Eocene (Inca phase) and Miocene (Quechua phase) compression. We correlated reported compressional and extensional stages with the multiphase evolution of mineral veins. We believe that at least some of the crust growth in the Western Cordillera may be related to a significant shortening of Mesozoic sedimentary complexes due to intense frontal fold-and-thrust tectonic processes. To the east, the intensity of folding and thrusting decreases, suggesting that observed shortening might be related to a very localized and narrow zones in the Western Cordillera.

A re-evaluation of the Variscan Front in Southern Ireland

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The Variscan Orogeny resulted from the collision between Gondwana and Laurussia, reaching its maximum intensity in the late Carboniferous. The resulting Tibetan-scale orogenic belt is a broad curvilinear feature that extends across most of Europe, as well as northern Africa and North America. The front of this orogeny is typically regarded as a narrow zone in the United Kingdom and Ireland, where tight folding and thrust-dominated tectonics switch to more open folding styles. However, in Ireland this front is poorly defined in outcrop and its exact location is still debated, as is the role of basement structures during deformation.

This study presents a re-evaluation of the development of the Variscan Fold Belt in the eastern Upper Devonian Munster Basin of Southern Ireland. Strain analysis and Anisotropy of Magnetic Susceptibility (AMS) studies confirm that penetrative grain-scale deformation is localised at major basin-bounding faults, which possibly acted as buttressing structures. This implies that the deformation of the Munster Basin was heavily influenced by pre-existing Caledonian and/or Acadian structures.

Quantifying and illustrating uncertainty on interpreted subsurface cross-sections: How to visualise uncertainty by zones and levels?

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Fold and fold-thrust structures commonly have a complex tectonic and structural history that is hard to interpret. This study aims to construct robust protocols to visualise and measure the uncertainty in subsurface geological interpretations of fold-thrust structures from sparse and incomplete datasets. The complex history of fold-thrust structures is hard to unravel from limited data, and 'accurate' interpretations are compounded by uncertainties inherent in subsurface structural interpretation. These challenges often result in the employment of heuristics, rules of thumb, and know solutions to subsurface interpretations that introduced bias. Greater subsurface control provided by galleries and shafts created for coal mining makes dataset from coal mines perfect for investigating interpretations of fold and fold-thrust geometries. However, illustrating and quantifying uncertainty in geological interpretations of subsurface cross-sections is still ambiguous. Here we show that high-resolution coalmine data provide an excellent opportunity to illustrate and quantify uncertainty using subsurface cross-sections of folds and fold-thrust geometries. Five zones have been used to display uncertainty in regional cross-section interpretations of late Carboniferous multi-layered stratigraphy through the Ruhr basin, coal measures of Germany. These five uncertainty zones are applied to horizon interpretations, with three uncertainty levels for fault interpretations. Together they form a critical part of the coalmine dataset. These uncertainty zones and levels, captured at the time of mining, allow the investigation of cross-section building and interpretation from level 1, where direct observations of the rock can be made, outwards, whilst illustrating growing uncertainty. Our uncertainty classification workflow is applicable to other sub-surface datasets and can be used to inform approaches to sub-surface interpretations elsewhere. We claim that quantifying uncertainty by zones and levels can provide a framework to reduce interpretation risk and improve visualisation of uncertainties in fold-thrust belt cross-sections.

Ductile strain and granite magmatism in the mid-crust of the Damara Orogen, Namibia

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The Damara Orogenic Belt in Namibia records NW-SE directed collision between the Congo and Kalahari Cratons at ~560-500 Ma. The orogen consists of oppositely dipping Northern and Southern Zones separated by a Central Zone.

The Central Zone consists of mid-crustal granulite-facies rocks exhumed from ~800^{O}C/4-5 kbar, and is characterised by a dome-and-basin structural pattern. Previous studies suggest that some of these domes are cored by a pre-Damaran basement complex, dated at ~1 Ga and ~2 Ga (U-Pb zircon). These rocks are overlain by metasedimentary units of the Damara Supergroup, although voluminous granite magmatism is also widely recognised. Various models have been presented to explain dome formation, including interference folding due to polyphase deformation, extensional core complex development, a single phase of constrictional flow, and tip-line folds located above blind thrusts. No consensus exists on which, if any, of these models is correct.

We report preliminary results of detailed field mapping undertaken during a Covid-19 enforced stay of 10 months in Namibia. Based on mapping of a ~15 km section of the Swakop River, previous interpretations of a pre-Damaran basement complex in the cores of domes visited appears incorrect. A distinct unconformity is not identifiable on dome limbs, and domes are overhwelmingly cored by widespread migmatitic gneisses and voluminous granitic intrusions. Migmatites are deformed to appear as augen gneisses, however these augen gneisses show textural continuity with cross-cutting leucogranite sheets which have previously been dated as Damaran in age. Consequently, zircons within these augen gneisses (U-Pb age of ~1 Ga and ~2 Ga) are almost certainly detrital in origin and inherited from partial melting of the Damara Supergroup; they do not necessarily indicate the presence of a pre-Damaran basement complex.

Seemingly syn-magmatic ductile strain is regionally pervasive throughout the dome cores and overlying metasedimentary rocks. A variety of asymmetric fabric patterns, magmatic schlieren, S-C structures, and features resembling ‘flow lobes’ give a consistent reverse sense of shear/vergence on both the east- and west-dipping limbs of upright domes. Stretching / rodding lineations have a consistent orogen-parallel and shallow NNE-SSW plunge. Leucogranite sheets overwhelmingly strike parallel to this stretching direction, and parallel to the NNE-SSW regional metamorphic fabric. Rock fabrics vary from locally L-tectonites with clear rodding lineations to locally S-tectonite flattening fabrics, although distinct ‘zones’ of L- and S-tectonites are not readily identifiable. Data collected to date seems compatible with a component of orogen-normal pure-shear compresson in addition to a component of orogen-parallel stretching. The latter may represent ‘tectonic escape’ parallel to the margins of the orogen, in a mid-crust too weak to tolerate the formation of high mountains. Alterantive tectonic models remain under investigation however.

Two orogens convergence and collision zone: A case study from the Central Caucasus, Georgia

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The Lesser Caucasus (LC) and Greater Caucasus (GC) orogens, which are among the best examples of collision-driven far-field deformations, are located in the northernmost part of the Arabia/Eurasia collision zone. Like the GC orogen, the LC is a double wedge orogen and forms a W-E-trending, bivergent thrust system. The Central Caucasus is one of the key regions of an apparent convergence zone between two orogens. The formation of the complex structure of the LC - GC convergence zone is governed by the northward and southward-directed thrusting. During the late Cenozoic, in response to collision between Arabia and Eurasian plates and their subsequent deformations, convergence between the LC and GC orogens took place in far-field zone.

Here I show the structural style of deformation of a convergence zone between LC retro-wedge and GC pro-wedge based on seismic reflection profiles. Fault-related folding and wedge thrust folding theories were used in the interpretation of seismic reflection profiles and construction of the structural cross-sections. Seismic profiles reveal the transition between convergence and the initial collision zone and exhibit structural variations along strike within the study area. The frontal part of the LC retro-wedge is represented by a shallow triangle zone and north-vergent structural wedge. The thrust front of GC pro-wedge is represented by south-vergent fault-related folds. Between the LC and GC frontal parts, the undeformed Kura foreland basin is located. The structure of the LC - GC initial collision zone is fairly complex. The orogens collision zone is represented by south-vergent imbricate thrusts. Under the triangle zone, two north-vergent structural wedges could be distinguished at depth. The lower structural wedge is composed by Paleocene-Middle Eocene strata and wedge tip is located in the lower part of Upper Miocene shales.

Historical Mtskheta earthquake (1275, Ms = 6.5), recent GPS, earthquakes and paleoseismic data indicate that the LC-GC convergence zone is tectonically fairly active. Near the LC - GC convergence zone is located Tbilisi city, where the south-vergent thrusts and blind thrust wedge of this collision zone represent a significant seismic hazard.

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Deformation history of a foredeep basin during its incorporation within an advancing orogenic wedge: the case of the Oligocene-Early Miocene Macigno Costiero Formation, southern Tuscany, northern Apennines, Italy

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Foredeep basins flanking mountain belts provide a clue for the interpretation of orogenic dynamics. When studying recent or active mountain belts, whose history is still well preserved in the foredeep sedimentary record, the kinematics of folding and thrust emplacement may be effectively unravelled through the analysis of deformation fabrics and of their overprinting relationships observed within syn-orogenic deposits. The Northern Apennines of Italy represents a classical ground for the study of orogenic processes through investigation of associated foredeep basins. Much information has been inferred by observations of stratigraphic and sedimentological features of syn-orogenic deposits, with comparatively little attention paid to their deformation structure, though with notable exceptions.

The Upper Oligocene Macigno Formation that crops out in the coastal section of SW Tuscany represents the sedimentary fill of a foredeep basin developed during the collisional stages that led to the construction of the Apennine mountain belt of peninsular Italy. The stratigraphic sequence consists of alternating sandstones and siltstones, that are affected by Km-scale contractional structures, namely SW-dipping thrusts and related NE-verging folds. An original field survey carried out along a superb coastal exposure, integrated with analysis of mesoscopic fabrics and their overprinting relationships, makes it possible to unravel a complex deformation history. Four main deformation stages are recognised: i) layer-parallel shortening A; ii) top-to-the-foreland shear B; iii) folding C, comprising the fold nucleation sub-stage C1 and the fold amplification sub-stage C2; and iv) thrust propagation D.

The sequence of recognized stages indicates a progressive deformation history of the Macigno Formation as it was incorporated within the evolving Apennine orogenic system. The kinematic history inferred from deformation fabrics and their overprinting relationships within Macigno Fm. deposits in SW Tuscany shows remarkable analogies with the structural evolution of foredeep sediments from other fold-and-thrust belts, yet with little deviations. These provide original information on the modes of accretion of foredeep deposits within evolving collisional belts and provide sound constraints to cross-section restoration through foreward modeling, thus contributing to an enhanced insight, understanding and elucidation of orogenic dynamics during mountain building.

The role of faults and post-extraction collapse on mine geothermal resevoirs.

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The heating and cooling sector represents a significant barrier to the UK govenments aim of carbon neutrality by 2050. However, mine water heating schemes could provide low carbon heat to millions of homes as well as rejuvinating ex-mining areas through the provision of jobs. For schemes to be succsessful the Mine Water Resevoir (MWR) needs to be able to sustain mine water extraction, whilst avoiding thermal breakthrough from shallow levels or from new schemes tapping the same heat source. In this work we outline geological uncertianties present in the MWR (Fig. 1a) and highlight how surface analogues of stall collapse and natural fault and fracture systems can inform our understanding of MWRs. Specifically the following will be discussed:

1. Conponents that make up a MWR (Andrews et al. *in Prep*).
2. Mine geometries and extraction methods from across the UK and how these impact resevoir properties (Andrews et al. *in prep*; Andrews et al. 2020a).
3. The effect faults have on the system, and how the internal structure and connectivity of faults studied in the field (Fig 1b) can inform our understanding of the hydrogeological properties of MWRs (Andrews et al., 2020b, Andrews, Shipton *in prep*).
4. How post-mining conditions can alter the MWR, and how overburden lithology will change this collapse process (Andrews et al., 2020a; Andrews et al., *in prep*).

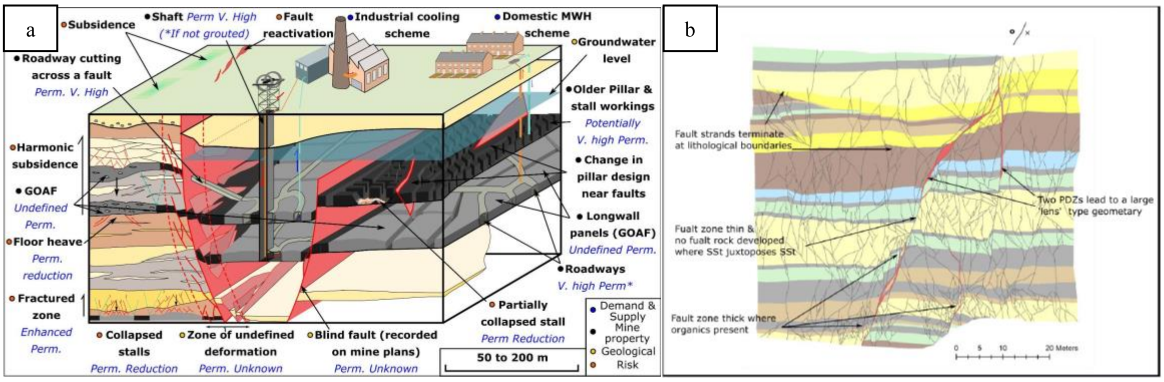

Fig. 1: a) Elements of a MWR, b) Fault exposed at Spireslack SCM (Andrews et al., 2020)

Refs: **1)** Andrews et al., (*in prep for Mine Water and the Environment)* The components and uncertainties within reservoirs associated with Mine Geothermal Energy Schemes. **2)** Andrews et al. (2020a) Collapse processes in abandoned pillar and stall coal mines: Implications for shallow mine geothermal energy. Geothermics. **88 (**101904). **3)** Andrews et al. (2020b) The growth of faults and fracture networks in a mechanically evolving, mechanically stratified rock mass: a case study from Spireslack Surface Coal Mine, Scotland. Solid Earth **11**, 2119–2140. **4)** Andrews et al. (*in prep for J. of Struct. Geol.*). The 'Trouble' with the carboniferous: Organic rich fault rock as a mechanism of fault zone weakening.

A Multi-proxy Approach for Fracture Network Quantification of Regional Fold and Thrust Structures for Geothermal Reservoir Characterisation

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Within the Horizon 2020 MEET project (*Multidisciplinary and multi-context demonstration of Enhanced Geothermal Systems exploration and Exploitation Techniques and potentials*) is to bring about this potential in previously considered unconventional geothermal reservoirs, focusing specifically on crystalline and meta-sedimentary Variscan basement rocks. One of the demo sites is located at the University of Göttingen with the reservoir at 4km depth, within the Variscan sedimentary basement.
With no research well and little in the way of seismic interpretation, the focus has been put onto the use of outcrop analogues within the Rhenohercynian zone to determine the potential of such a reservoir. The focus of this study is primarily within the Clausthal Culm Fold Zone (CCFZ) in the Western Harz Mountains, comprised of NW verging folds of Lower Carboniferous greywackes and slates. With the complexity of the structural and lithological attributes of the reservoir, along with limited subsurface data, a methodology has been established to characterise the main target areas within the CCFZ for the collection of fracture network parameters for use in fluid flow and DFN models. By collecting field data in various forms such as drone images and 3D outcrop models, the structural and lithological situations can be characterised, and an overview of the changes of the fracture network characteristics can be quantified. Throughout the analogue site fracture parameters are collected, aerial intensity, connectivity and orientation, at sites that correspond to the structural and lithological situations listed in Fig.1.

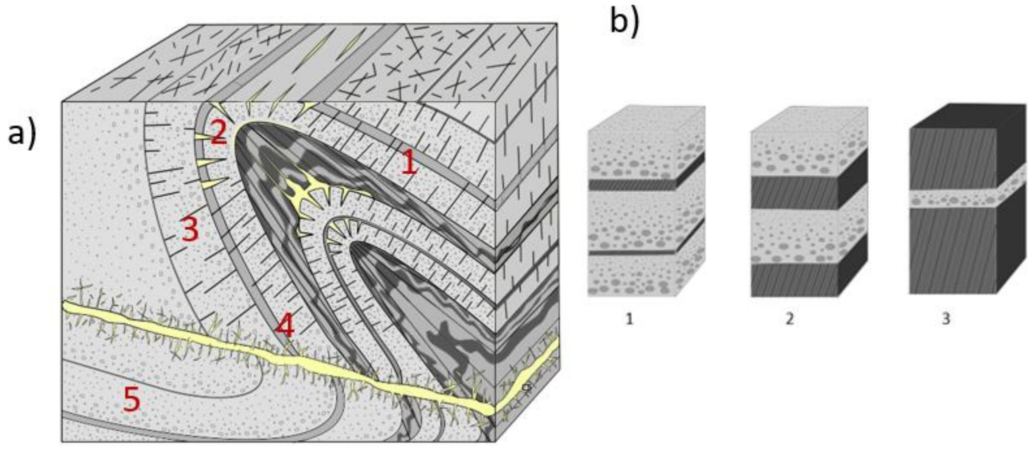

Figure 1- a) Conceptual diagram of a reservoir-typical, scale invariant fold and thrust structure with 5 representative structural situations. 1 - Forelimb, 2 - Hinge zone, 3 – Overturned Limb, 4 – Thrust Zone, 5 – Low Angle Forelimb. b) Conceptual lithological situations 1 – Thick greywacke beds with little to no slate, 2 – Greywacke beds with thicker slate intercalations, 3 – Thick slate beds with small greywacke beds.

This method focuses on the fracture characteristics based on their relationship to the lithology and placement within a fold rather than physical location, allowing for a more holistic approach for a potential development reservoir permeability in cases where subsurface data is limited.

Surface and subsurface fault mapping of the Flamborough Head Fault Zone to inform groundwater resource management

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The Flamborough Head Fault Zone (FHFZ) marks the southern limit of the Cleveland Basin and the northern margin of the Market Weighton Block, England. It is a regionally-significant structural zone which has a complex history of reactivation during both extensional and compressional tectonics during the Mesozoic and Cenozoic. It is predominantly comprised of east-west trending faults which form a graben, bound in the north by the listric Bempton Fault and in the south by the Langtoft Fault. The FHFZ is transected by the north-south trending faults of the Hunmanby Trough, the onshore extension of the Peak Trough. To the west, FHFZ links with the Howardian Fault System and offshore, in the east, it links with the north-south trending Dowsing Fault. The FHFZ is well exposed and described from coastal cliff sections at Flamborough Head but the inland development of the faults has hitherto been poorly explored predominantly due to limited inland-exposure.

The region around the FHFZ is underlain by the Chalk Group which is a principal aquifer and provides the main source of water supply in East Yorkshire. The geometry and physical characteristics of the Chalk succession, including the effects of faulting, influence groundwater flow across the region. A multi-faceted approach to geological mapping has been undertaken in the region by the British Geological Survey, in collaboration with the Environment Agency. Remote sensing, targeted field mapping, palaeontological analysis, passive seismic and 2D onshore seismic interpretation have been integrated to understand the inland architecture of the FHFZ and to produce a revised map of the Chalk succession in the region. Combining these techniques has enabled us to bridge the gap between the surface geology and deeper subsurface structure, increase our understanding of the geology of the region and produce an improved conceptual model at a range of depths which will be used to better manage water resources.

A range of modern data and recent geological research highlight that considerable changes can be made to the region's current geological maps and subsurface understanding. Ensuring a consistent and modern understanding of the geology is key for up-dating groundwater models to enable more confident decisions about land-use, water management and environmental regulation.

Stochastic Allan Diagrams for Juxtaposition Analysis

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Juxtaposition analysis—where the impact of cross-fault stratigraphic juxtapositions on fault seal and cross-fault fluid flow is evaluated—is a critical part of typical fault seal analysis workflows. A standard tool to carry out juxtaposition analysis has been the Allan Diagram (also known as a fault-plane section or a 2D fault plane map). Using this diagram, the stratigraphy that intersects each side of a fault is visualized on the fault plane, allowing a rapid assessment of critical juxtaposition windows. The traditional Allan Diagram only allows visualization of a single stratigraphic realization, meaning that it is difficult to evaluate the impact of stratigraphic uncertainty on cross-fault juxtapositions without a time-consuming analysis of large numbers of diagrams. This contribution outlines a workflow for creating stochastic Allan Diagrams to visualize cross-fault juxtapositions and output a distribution of predicted highest elevation sand-sand juxtapositions along a fault for multiple stratigraphic realizations. The workflow is demonstrated on a test dataset. The methodology described here can be used to inform the assessment of trap-and-seal risk in hydrocarbon exploration, carbon capture, and storage contexts.