



# ABSTRACT VOLUME

University of Hull, 7<sup>th</sup>-9<sup>th</sup> Jan  
2020

Convenors: Dr Eddie Dempsey, Dr Anna Bird,  
Dr Jon Pownall, Prof Dan Parsons

# TSG 2020, Hull

	Monday	Tuesday	Wednesday	Thursday
	6th Jan	7th Jan	8th Jan	9th Jan
09:00	TSG FIELD TRIP – coach departs 8am from outside Middleton Hall on university campus	REGISTRATION / coffee	arrival	arrival
09:15		Welcome	Uncertainties in break-up markers along the Iberian – Newfoundland conjugate margin illustrated by newly available seismic data - Annabel Causer	Numerical investigation of continental extension in heterogeneous orogenic lithosphere, constrained by observations from the Labrador Sea M. Gouiza
09:30		Interactions of multi-scale fracture network within different sedimentological domain of an isolated carbonate platform at Latemar: implication for fluid-flow - O.A. Igboke	Techniques to validate subsurface interpretation for folds and fold-thrust related geometries using examples from coalmine dataset in lower Rhine basin - Ruhr sub-basin, Germany: Ramiy Abdallah	Tectonic evolution of Anglesey and adjacent mainland North Wales: accretion of peri-Gondwanan elements in the UK sector of Iapetus - Leslie, A.G.
09:45		Relating slip morphology and kinematics of a liquefaction event to flow evolution - Rebecca Macaskill Robertson	Initiation of the Great Glen Fault Zone as a Dextral Transform Fault during the Scandian orogeny - Evidence from the Rubha na h-Earba Fault and Linnhe Intrusion - E Dempsey	Basin structural analyses of Lower and Middle Benue Trough of Nigeria derived from the analysis of remote sensing, gravity and aeromagnetic data Yenne E.Y.
10:00		Seismic Analysis and Volumetric Estimations of Mass Transport Deposits in the Rockall Trough. - Roseanna Bentley	Stretching transform faults in the Mediterranean region. Ernest H. Rutter	The nature and origin of structures within the Burren, County Clare, Ireland. John Walsh
10:15				
10:30		coffee	coffee	coffee
10:45		Regional tectonic implications on the tectonic contact at Zannone Island, Italy - Curzi M.	Geomorphic expressions of collision tectonics in the Qilian Shan, North Eastern Tibetan Plateau - Katharine Groves	Dating faults, fractures, and fluids with U-Pb calcite geochronology (1): Strategies, progress, and pitfalls Nick M W Roberts
11:00		Characterising near-fault coseismic and post-seismic deformation from point clouds at different scales: the 2016 Mw 6.6 Norcia earthquake (Central Italy) Bob Elliott	Diachronous Tibetan Plateau landscape evolution derived from lava field geomorphology Mark Allen	Dating faults, fractures and fluids with U-Pb calcite geochronology (2): Application to contrasting fracture and fluid-flow modes of the Cleveland Basin Jack Lee
11:15		Fracture distribution within a carbonate hosted relay ramp: insights from the Tre Monti fault, (Central Italy) - Mercuri, M	Reconciling geophysical and petrological estimates of the thermal structure of southern Tibet T.J. Craig	Fracture Network Characterization of the Culm Fold Zone, Western Harz Mountains – Germany, as a Means to Extract Geothermal Reservoir Parameters Katherine FORD
11:30		Local stress amplifications associated with viscous shear zone networks trigger lower crustal earthquake nucleation Lucy Campbell	The interplay between deformation and metamorphism in lawsonite eclogites from the Yukon-Tanana Terrane, Yukon Territory, Canada and implications for rheological behaviour during subduction and exhumation - Carly Faber	Hydrogen storage and faults: learning from natural analogues Christopher J. McMahon
11:45		KEYNOTE: Deformation at Continental Thrust Faults Before, During and After Major Earthquakes - Prof Tim Wright	KEYNOTE: To localize or not to localize that is the question: Deformation behaviour of the crust – field studies and numerical simulations - Prof Sandra Piazolo	KEYNOTE: Structural Geology in Geothermal - Teaching a New Dog Old Tricks - Dr Dave McNamara
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EVENING	ICEBREAKER The Com Exchange, Hull Old Town from 7:30	SCIENCE IN THE PUB: PUBLIC Q&A "The role of structural and tectonics research in our green future"	CONFERENCE DINNER Tapasya @ marina Humber Dock from 7 pm	2-3

# Keynote

## Abstracts

## The Rock Record of the Earthquake Cycle

Christie Rowe + many friends and collaborators

Three phenomena differentiate seismic slip in faults from displacement at sub-seismic slip rates in ancient faults: transient temperature rise, extreme stressing rates, and catastrophic slip weakening. Distinctive and diagnostic changes in the structure and composition of fault rock and wall rock resulting from these phenomena can permanently preserve a record of past earthquakes.

Changes to fault rocks caused by seismic slip include phase changes, grain size reduction, mineral breakdown, melting, and metamorphism. As most of these changes are permanent, one might expect that after a reasonable amount of time, earthquake rocks should dominate the crust! Of course this is not the case — coseismic rocks and structures are fragile and easily destroyed or overprinted by afterslip (which is increasingly recognized as potentially similar in displacement as the earthquakes themselves) or by creep and healing processes during inter-seismic periods. Afterslip is harder to pinpoint in exhumed faults as it may be accommodated either by slip on discrete faults or by strain in a volume of rock, by a variety of mechanisms. Healing describes the longer-term (days-centuries) processes which contribute to re-locking and re-loading of faults during earthquakes. Faults are by definition weaker than the surrounding rocks, so it is actually remarkable that faults can lock up at all. Recognizing creep and healing as driven by solution-precipitation creep offers one possible explanation for why faults lock. By recognizing these different processes in the rock record, we can probe the earthquake cycle for information that can't be obtained seismologically or geodetically over the timescale of human observation.

## Structural Geology in Geothermal - Teaching a New Dog Old Tricks

David McNamara – Department of Earth, Ocean and Ecological Sciences, University of Liverpool

Many high temperature, conventional and enhanced, geothermal reservoirs are hosted in reservoir rocks with low intrinsic permeability. As such, successful development of these resources relies on understanding the role subsurface structures, such as fractures and faults, play in reservoir permeability. There are two crucial research aspects to developing our understanding of structural permeability in geothermal resources: 1) the development of a comprehensive understanding of geothermal geomechanics, and 2) permeability alteration via geothermal fluid-rock interaction. While many techniques for investigating these research fields exist, they require modification in both underpinning science and method for use in geothermal settings, and often novel, innovative, scientific approaches are required.

Borehole imaging is regarded as a key dataset in the development of a robust reservoir geomechanical model. It is only within the last decade that the technology required for borehole image log acquisition in high temperature geothermal boreholes has been developed and deployed. Since then the development of innovative geothermal image log data processing and interpretation has allowed structural geologists to make advances in characterising the subsurface structure and stress state of many geothermal fields. The geothermal centres in the Taupo Volcanic Zone are one such resource that has become much better characterised in terms of its geomechanics, facilitating better geological, geomechanical, and fluid flow modelling. New borehole image datasets reveal previously unknown structural orientation heterogeneity at a variety of scales within individual geothermal fields, describe variability in in-situ horizontal stress directions, and when combined with other logging data have pinpointed structures that currently contribute to geothermal well flow.

The same fractures and faults, which operate as interconnected, open, fluid flow pathways in geothermal fields, can also behave as fluid flow barriers when fluid-rock interaction results in mineral precipitation within these structures. While common in many aspect of geoscience research, the application of microstructural investigation techniques to analyse crystallographic and chemical properties of reservoir scaling minerals in geothermal systems is rare. The use of these geological techniques in geothermal systems is providing new information on evolving geothermal reservoir conditions, mineral nucleation and growth controls in fracture sealing, and on reservoir scaling processes and rates.

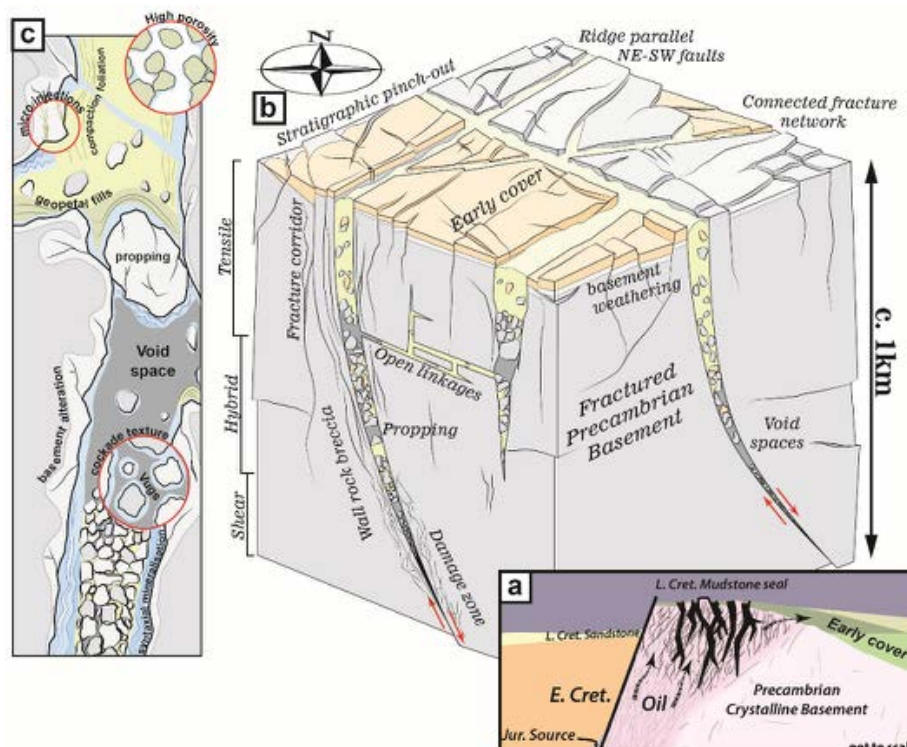
Advances in the application of structural geology at both the macro and microscale within geothermal systems are proving important to answer important geological and operational questions. As geothermal continues to grow as an international industry, and given its importance as part of the solution to decarbonising our society, it is crucial to continue to transition skillsets and methodologies to this sector, as well as innovate and develop geoscience specifically for geothermal advancement.

# The Lancaster Field: the anatomy and structural evolution of a fractured basement reservoir

Holdsworth, R.E.<sup>1,2</sup> Trice, R.<sup>3</sup>, Hardman, K.<sup>1</sup>, McCaffrey, K.J.W.<sup>1,2</sup> Morton, A.<sup>4</sup>, Frei, D.<sup>5</sup>  
Dempsey, E.<sup>6</sup>, Bird, A.<sup>6</sup>, Rogers, S.<sup>7</sup>

1 Department of Earth Sciences, Durham University, DH1 3LE, UK; 2 Geospatial Research Ltd, Durham DH1 4EL, UK; 3 Hurricane Energy plc, Godalming, GU7 2QN, UK; 4 HM Research, St Ishmaels SA62 3TJ and CASP, University of Cambridge, CB3 0UD, UK; 5 Department of Earth Sciences, University of the Western Cape, 7530 Bellville, South Africa; 6 Department of Geography, Geology and Environment, University of Hull, HU6 7RX, UK; 7 Golder Associates Ltd, Vancouver, Canada

**Abstract:** Hosting up to 3.3 billion barrels of oil in place, the upfaulted Precambrian crystalline rocks of the Lancaster Field, offshore west of Shetland, give key insights into how fractured hydrocarbon reservoirs can form in such old rocks. The Neoarchaeon (ca 2700-2740 Ma) charnockitic basement is cut by deeply penetrating oil-, mineral- and sediments-filled fissure systems seen in geophysical and production logs, and thin sections of core (Figs 1a-b). Mineral textures and fluid inclusion geothermometry suggest that a low temperature (<200 °C) near-surface hydrothermal system is associated with these fissures. The fills help to permanently prop open fissures in the basement, permitting the ingress of hydrocarbons into an extensive well-connected oil saturated fracture networks (Figs 1b-c). U-Pb dating of calcite mineral fills constrains the onset of mineralization and contemporaneous oil charge to the mid-Cretaceous onwards from Jurassic source rocks flanking the upfaulted ridge (Fig 1a). Late Cretaceous subsidence and deposition of mudstones sealed the ridge, and was followed by buoyancy-driven migration of oil into the pre-existing propped fracture systems. These new observations provide an explanation for the preservation of intra-reservoir fractures ('joints') with effective apertures of two meters or more, thereby highlighting a new mechanism for generating and preserving fracture permeability in sub-unconformity fractured basement reservoirs worldwide.



To localize or not to localize that is the question:

Deformation behaviour of the crust – field studies and numerical simulations

S. Piazzolo<sup>1</sup>, R. Gardner<sup>2</sup>, N.R. Daczko<sup>2</sup>, H. Ghatak<sup>2</sup>, D. Silva<sup>2</sup>, L. Evans<sup>2</sup>, T. Raimondo<sup>3</sup>

<sup>1</sup>*School of Earth and Environment, University of Leeds, UK*

<sup>2</sup>*Department of Earth and Planetary Sciences, Macquarie University, Australia*

<sup>3</sup>*Natural & Built Environments & Future Industries Institute, University of S Australia, Australia*

It is generally believed that strain localization fundamentally controls not only the local but also the bulk rheological response of a material. Many studies have shown that strain is easily localized in a polyphase rock, especially if the rock undergoes syntectonic weakening processes. In the field, there is clear evidence that different patterns of strain localization are observed. Could these patterns, including the width of individual shear zones yield important insights into the state of the rocks in which these patterns are observed? At the same time, there is ample field evidence for distributed, rather than localized deformation at the outcrop to hundreds of square kilometre scale. In these areas, distributed strain is evidenced by the presence of continuous foliations and a lack of distinct high strain zones. But how do these areas form? If we see distributed strain in the field what does it tell us about the rheology of the rock mass we are investigating? At a continental scale, the most extreme localization occurs where mountain belts form. “Classically” most mountain belts formed at plate boundaries, but some, form instead in plate interiors, the so-called intracontinental orogens.

We use numerical simulations combined with field evidence (Silva et al., 2018, Gardner et al. 2017, 2019) to explore the strain localisation patterns formed, including the conditions at which deformation is distributed and how intracontinental orogens form. We identify three strain localization regimes and the conditions of their formation. Regime I is characterized by distributed strain. It forms either where deformation-induced interconnection of a weak phase is not possible, or the initial weak phase area is intermediate to high. Regime II is characterized by variably distributed areas of strain localization, and it develops if the initial proportion of weak phases is intermediate. Regime III exhibits significant strain localization, and only develops if the initial proportion of weak phases is relatively low. If in Regime III stress related dynamic weakening is modelled, strain quickly localizes into “weak layers”, where an increasing proportion of weak material causes interconnection between these layers, thereby increasing the anastomosing character of the shear zones.

At the continental scale, intracontinental orogeny is strongly related to reactivation of pre-existing structures and the presence of rheologically weak areas. In the case of our field example, the Alice Springs Orogen of Central Australia, the presence of melt acts as the “weak phase” in the deep crust enabling strain localization at the continental scale.

# Deformation at Continental Thrust Faults Before, During and After Major Earthquakes

Wright, T.J.<sup>1</sup>, Ingleby, T.<sup>1</sup>, Hooper, A.<sup>1</sup>, Craig, T.J.<sup>1</sup>, Weiss, J.R.<sup>1</sup>, and Elliott, J.R.<sup>1</sup>

1. COMET, School of Earth and Environment, University of Leeds, Leeds, United Kingdom

Much of our understanding of the earthquake deformation cycle is derived from observations at major strike-slip faults. By contrast, relatively few long-term geodetic data sets exist at continental thrust faults, and it remains unclear whether ideas developed at strike-slip faults are applicable to other fault systems. Here, we use geodetic observations from convergent zones in Nepal and Pakistan where major earthquakes have occurred in the geodetic era. We investigate the geometries and frictional properties of the thrust systems, and discuss the implications for mountain building.

We first examine the Himalayan frontal thrust system, where a major earthquake occurred in 2015 (M7.8 Gorkha, Nepal). Despite extensive study, the geometry of the fault system remains controversial. Here, we use interseismic, coseismic and postseismic geodetic data to investigate the proposed down-dip geometries. We find that kinematic and dynamic models constrained by geodetic data alone cannot fully discriminate between the previously proposed fault geometries. We find different frictional properties down-dip of the coseismic slip patch to up-dip, and confirm that the up-dip portion of the thrust remains locked. By examining interseismic, coseismic and postseismic slip, we assess the overall slip budget of the system and discuss the implications for mountain building.

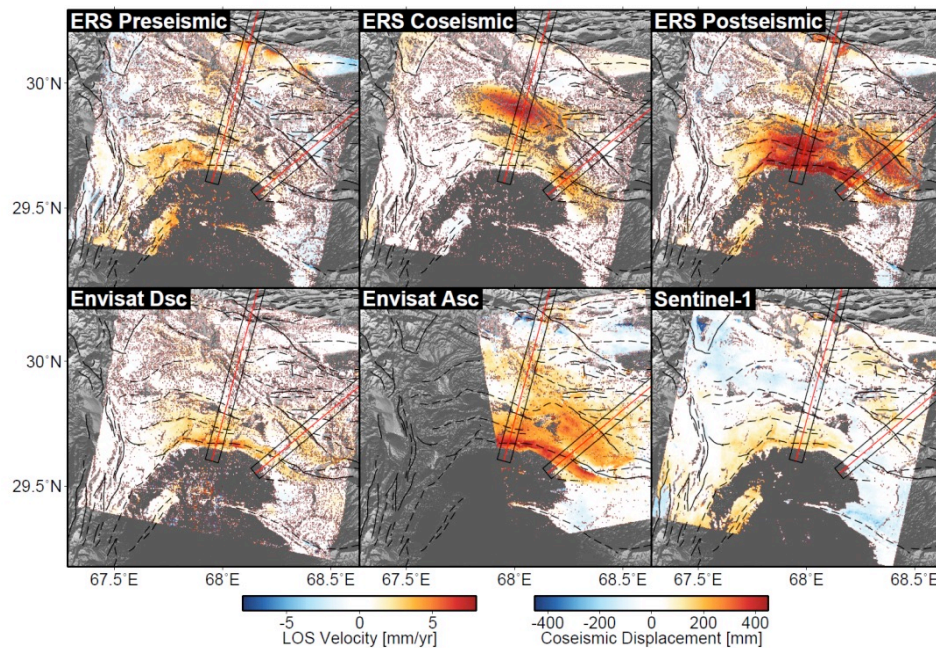


Figure 1: Deformation occurring before, during and after a M7.1 earthquake doublet in Pakistan in 1997, observed with InSAR from ERS-1, ERS-2, Envisat, Sentinel-1A and Sentinel-1B.

We also show results from the Sibi area of the Sulaiman fold-and-thrust belt in Pakistan, where an earthquake doublet occurred in 1997. Here we combine deformation data spanning 25 years from ERS-1, ERS-2, Envisat, Sentinel-1A and Sentinel-1B to give a long-term geodetic history for the area, including interseismic deformation measured before the earthquake, coseismic deformation, and postseismic deformation (Figure 1). We find that afterslip dominates the post-seismic deformation and that this slip occurs both up-dip and down-dip of the coseismic rupture. We investigate the relationship between short-term deformation and topography and use the data to constrain the frictional properties of the fault system. We discuss the implications of our results for earthquake hazard and the long-term evolution of topography in the continents.

# Oral Abstracts

## **Interactions of multi-scale fracture network within different sedimentological domain of an isolated carbonate platform at Latemar: implication for fluid-flow**

O.A. Igbokwe<sup>1,2,\*</sup>, J.J. Timothy<sup>3</sup>, M. Mueller<sup>1</sup>, K.I. Chima<sup>2,4</sup>, G. Bertotti<sup>5</sup>, Adrian Immenhauser<sup>1</sup>,

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<sup>2</sup> Department of Physics, Geology and Geophysics, Alex Ekwueme Federal University Ndufu-Alike, Ikwo, P.M.B. 1010, Abakaliki, Ebonyi State, Nigeria

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Carbonate platforms accommodate pervasive multi-scale fracture networks in their deformed condition regardless of the scale of the deformation. These fracture networks exert major impact on the mechanical and flow behaviour in different sedimentological compositions of the platform bodies. A multi-scale fracture network arrangement in and around an isolated carbonate platform from Latemar – in the western Dolomites, northern Italy, is investigated focusing on characterizing geometry, patterns of stress fields, strain and different fracture interactions from the limestone lithofacies to their dolomitized equivalents. The interior of the Latemar carbonate platform presents an excellently exposed outcrop analogue for subsurface reservoirs of isolated carbonate build-ups affected by dolomitization and igneous activities. Here, we expand on the observed interaction between multi-scale fractures and fluid within the platform's different sedimentological domains i.e. limestone lithofacies and dolostones, using outcrop structural analysis, drone imagery and fluid-flow modelling.

The studied Middle Triassic Latemar platform is moderately deformed by the combination of a dense framework of high-angle mode I fractures (joints and veins), low-angle reverse conjugate faults, magmatic dikes and hybrid fractures. At the base of the platform, the low-angle reverse conjugate faults relate to sub-vertical stylolites and sub-horizontal joints that were formed in a stress field characterized by horizontal  $\sigma_1$  and vertical  $\sigma_3$ . Whereas the conjugate hybrid fractures, at the top of the platform, are associated with sub-vertical tectonic stylolites that were sustained in a stress field dominated by sub-horizontal  $\sigma_1$  and sub-vertical  $\sigma_2$ .

Results from the modelling suggest that fractures within the limestone and dolostone domains are correlated in terms of geometry and topology. These fractures act as the principal conduits for fluid-flow, and contribute to the dolomitization of the precursor limestone mostly when the fractures are open during the burial diagenesis. Numerical results further show that the geometrical and topological features of fractures including orientations, lengths, aperture and connectivity are critical in the preferred flow directions.

This study provides a robust analogue for hydrocarbon exploration and production from an isolated carbonate platform with limestone and dolostone reservoirs, particularly where these lithologies are intensely deformed with associated multi-scale fracture networks.

# Relating slip morphology and kinematics of a liquefaction event to flow evolution

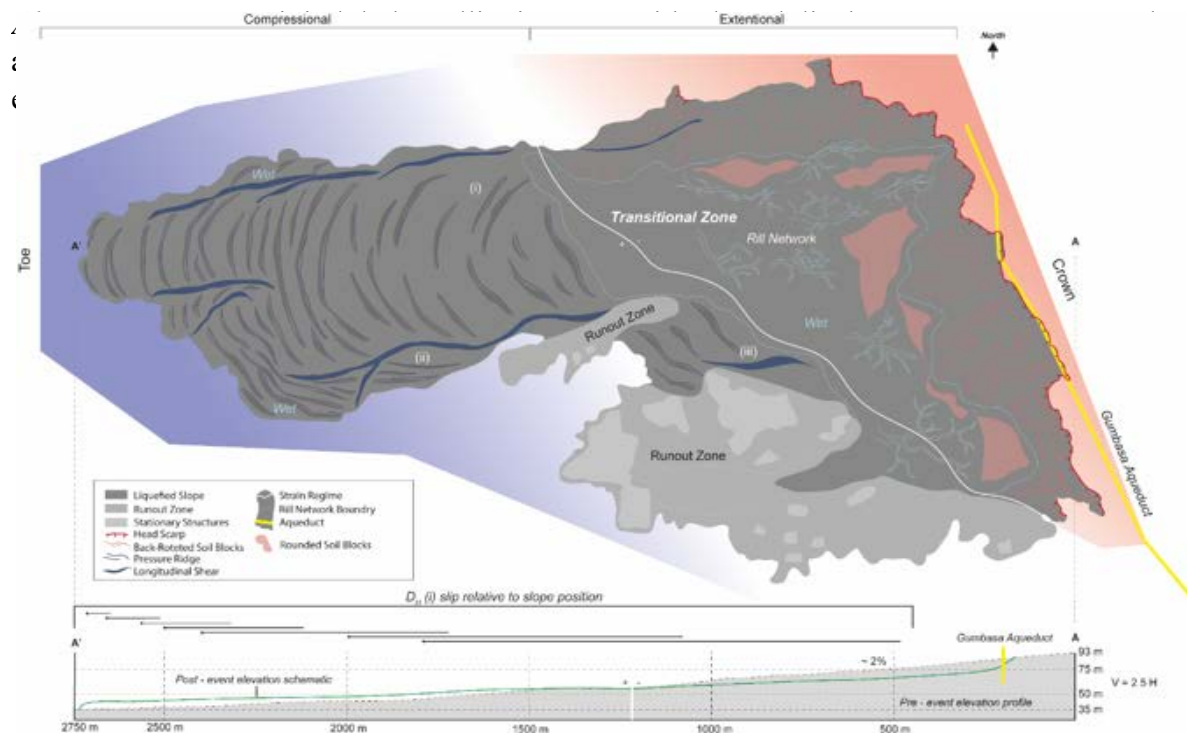
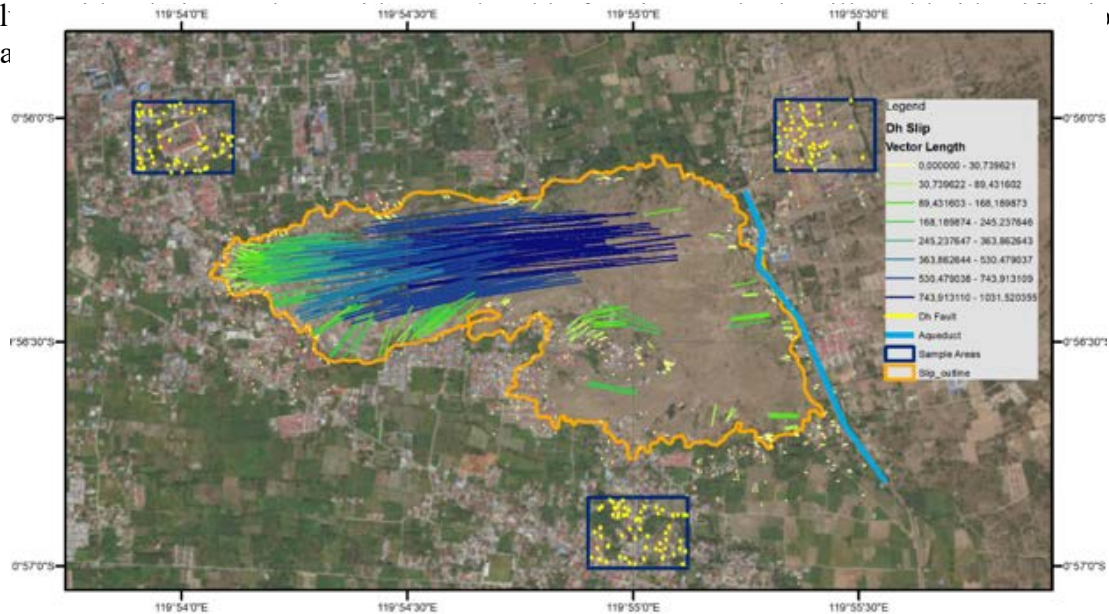
Rebecca Macaskill Robertson<sup>1\*</sup> & Robert Butler<sup>1</sup>

<sup>1</sup>Department of Geosciences, University of Aberdeen, Meston Walk, AB24 3UE, UK

\*Corresponding author (e-mail: r.robertson.14@aberndeen.ac.uk)

Liquefaction of water saturated sediment on the low gradient slopes of Palu valley, Sulawesi (Indonesia), destroyed neighbourhoods and resulted in massive loss of life. A  $M_w$  7.5 earthquake in September 2018 applied seismic cyclic loading to unconsolidated alluvial deposits, inducing increased pore fluid pressure resulting in previously solidified and saturated sediments acting as pseudo-plastic flows. Artificial shallowing of local water table for rice paddy irrigation, a common practice across Southeast Asia, holds strong correlation to liquefaction occurrence observed in this study. Displacements across these liquefied slope failures have magnitudes up to 1000 m, making application of computational pixel picking displacement quantification impossible. Here we define a method of hand-picking with error reduction and fault movement compensation. Displacement vectors were then related to observed liquefaction slip morphology to produce slope failure evolutions. Understanding the dynamics of liquefaction based slope fail

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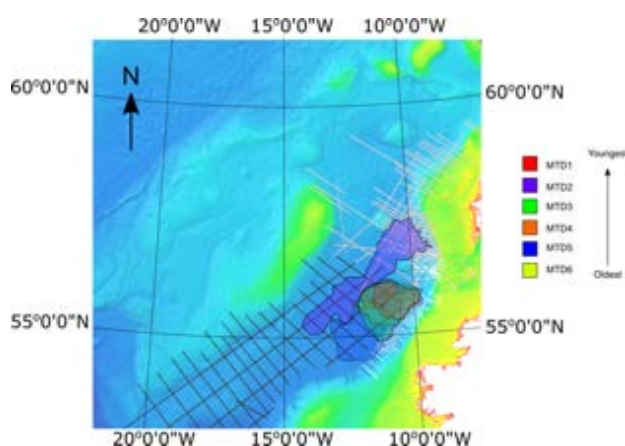
## Seismic Analysis and Volumetric Estimations of Mass Transport Deposits in the Rockall Trough.

*Roseanna Bentley, Murray Hoggett and Stephen Jones*  
*University of Birmingham*

Mass transport deposits (MTDs) are submarine landslides that move downslope, translating unconsolidated sediments along a basal shear surface. Deep water MTDs are observed from slope to basin-floor in submarine basins around the world and form a fundamental process in the evolution of the world's margins, accounting for up to 70% of the stratigraphy in some places.

The study encompasses the Rockall Trough, a NNE–SSW trending, elongate, 2–3 km-deep bathymetric depression situated on the continental shelf west of the UK and Ireland. Six MTDs have been identified for the first time using a large grid of public and proprietary 2D seismic data that spans the entire trough.

We recognise 2 overarching MTD systems. The first, consists of MTDs 1,3,4,5 and 6, which are debris flows and slumps starting from the low-slope and ceasing in the SE basin floor. The second system comprises MTD2 only, a slump deposit originating from the NE Rockall Trough; which may be part of the Peach Debrite Complex but is considerably larger than previously documented. The estimated ages of the 6 MTDs range from 160 ka–3 Ma. The largest deposit (MTD5) has an area and volume of 21,890 km<sup>2</sup> and 2,184 km<sup>3</sup> respectively, making it among the largest MTD so far reported. Kinematic indicators—geological structures that document the mode of movement at the time of deposition—were used to understand the rheology, type and movement direction of each MTD. We evaluate the mechanisms that triggered these landslides, including rapid sedimentation of the eastern margin of the Rockall Trough, the proximity to the Anton-Dohrn Lineament and glacial influences from the Mid-Pleistocene onwards.



*Bathymetric base-map showing the location and extent of the six MTDs documented by this study. Outline of Irish coastline (SE corner) conveys the location within the NE Atlantic. Coloured lines represent the different seismic surveys: black – Irish Petroleum Affairs Division, light pink – UK Oil and Gas Authority, white – proprietary data kindly provided by Spectrum.*

## **Regional tectonic implications on the tectonic contact at Zannone Island, Italy**

Curzi M., Billi A., Carminati E., Albert R., Aldega L., Bernasconi S., Boschi C., Caracausi A., Cardello L., Conti A., Drivenes K., Franchini F., Gerdes A., Rossetti F., Smeraglia L., Sørensen B E., Van der Ielij R., Vignaroli G. & Viola G.

Zannone is a very important island, located in the Neogene-Quaternary extensional domain of the Tyrrhenian back-arc basin, as it is the unique spot where the Paleozoic (?) crystalline basement is hypothesized to be exposed in central Apennines. The exposure of such hypothetical basement in the Zannone Island is very problematic as it implies very large normal displacements (> 3 km) along surrounding faults. No such displacements are known along faults close to Zannone Island.

In this work, we study the hypothetical Paleozoic (?) crystalline basement exposed in the Zannone Island with the main aim of understanding its geological nature and relationships with the surrounding rocks. We use a multidisciplinary approach including 1) field survey; 2) petro-textural observations; 3) petrologic analyses of the host rocks; 4) microthermometry on fluid inclusions; 5) geochemical analyses of stable and clumped isotopes; 6) analyses of minor gaseous species (He, Ne, and Ar concentrations and isotope ratios) in fluid inclusions; 7) U-Pb geochronology of syn-tectonic calcite; 7) K-Ar dating of syn-kinematic clay minerals, and 8) X-ray diffraction (XRD) analysis of the clay size fraction.

Our results show that the hypothetical Paleozoic (?) crystalline basement exposed on the Zannone Island is, instead, represented by siliciclastic rocks of very low metamorphic grade. This is testified by the presence of chloritoid and by the observed incipient foliation marked by fine-grained white micas and disposed parallel to the bedding. The contact between such siliciclastic rocks and the overlapping Triassic Dolostones is represented by a low-angle thrust cut by sets of high-angle normal faults with associated calcite mineralizations. K-Ar dating on clay minerals in fault gouge reveals a strong contamination of K- bearing minerals from the protolith. In detail, we obtained an age of ~22 Ma which reveals that at least one event of authigenesis (i.e. fluid-assisted tectonic activity) occurred in Zannone Island <22 Ma ago. U-Pb dating on sin-tectonic calcite mineralizations allowed to constrain the compressional deformation and subsequent normal faulting in the study area at around 7 Ma. This result is consistent with the 1) described emplacement of imbricate thrust sheets onshore close to Zannone Island and 2) syn-tectonic sediments-filling basins observed by seismic reflection studies.

Petrographic observations on fluid inclusions in tectonic quartz and calcite mineralizations allowed to determine that such inclusions were entrapped at the same time and therefore at the same depth. Microthermometry on fluid inclusions allowed to constrain a wide range on P-T entrapment conditions. For this reason, we highlighted a transition from lithostatic toward hydrostatic pressure during precipitation of syn-tectonic quartz and calcite mineralizations. Microthermometry on fluid inclusions highlighted also the presence of two fluids during tectonic processes. One characterized by low salinity (as NaCl equivalent) and one by high salinity (as NaCl equivalent). Coupled stable isotopes analyses on the same calcite mineralizations, we highlighted a mixing between meteoric and deep fluids, as testified by the high spread of calculates values of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ .

## Uncertainties in break-up markers along the Iberian – Newfoundland conjugate margin illustrated by newly available seismic data

Annabel Causer, Lucia Perez-Diaz, Graeme Eagles and Jürgen Adam

The Iberian-Newfoundland conjugate margins are one of the most extensively studied non-volcanic rifted margins in the world. In recent years, researchers have focused their efforts at better understanding the earliest stages of continental rifting, often relying heavily on the identification of so-called “break-up features” imaged in seismic profiles or interpreted from potential field data. Along the Iberian-Newfoundland margins, widely used break-up markers include interpretations of old magnetic anomalies from the M-Series, as well as the J-anomaly, believed to mark the occurrence and spatial extent of first oceanic lithosphere. However, uncertainties in the location and interpretation of these features have led to discrepancies between plate models based on them. These discrepancies are illustrated by differing depictions of the modelled palaeopositions of Iberian and Newfoundland during the early Cretaceous as well as by the proposed timing of first seafloor spreading between the two.

We use newly acquired seismic data from the Southern Newfoundland Basin (SNB) to assess the suitability of ‘break-up’ markers along the Iberian – Newfoundland Margin for plate kinematic reconstructions. Our data shows that basement associated with the younger M-Series magnetic anomalies is comprised of exhumed mantle and magmatic additions, and most likely represents transitional domains and not true oceanic lithosphere. Similarly, our data also allows us to show that the high amplitude of the J Anomaly is associated to a zone of exhumed mantle punctuated by significant volcanic additions, and at times characterised by interbedded volcanics and sediments within the SNB. Magmatic activity in the SNB at a time coinciding with M4 (128 Ma), and the presence of SDR packages onlapping onto a basement fault suggest that, at this time, plate divergence was still being accommodated by tectonic faulting. We conclude that a different approach, not reliant on the identification of extended continental margin features, is required in order to robustly constrain North Atlantic tectonics pre-M0 (~121 Ma) times.

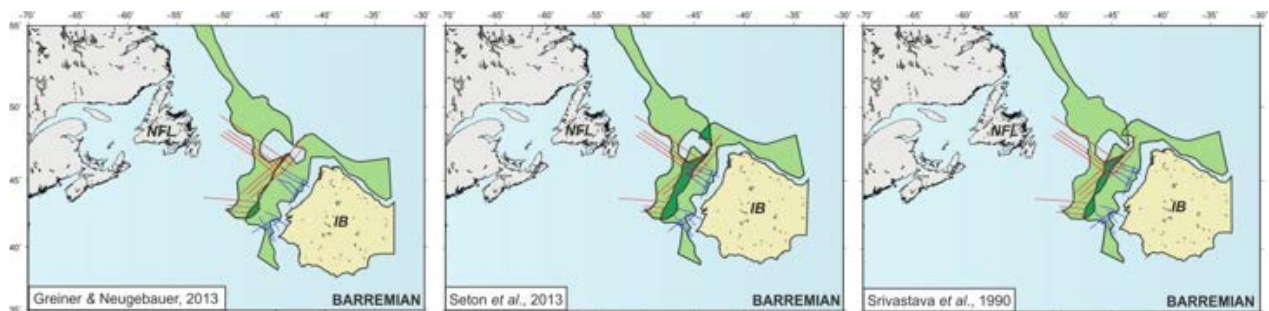


Plate kinematic reconstruction at the ‘pre drift stage’. Green outline represents the minimum and maximum Continental Ocean Transition Zone taken from Eagles *et al.*, 2015; dark green shows the overlap of transition zones. Red and blue lines show a selection of TGS’ seismic data from the Newfoundland and Iberian margins.

## Dating faults, fractures and fluids with U-Pb calcite geochronology (2): Application to contrasting fracture and fluid-flow modes of the Cleveland Basin

Jack Lee<sup>1,2\*</sup>, Nick M W Roberts<sup>2</sup>, Jonathan Imber<sup>1</sup>, Robert Holdsworth<sup>1</sup>, Andy Aplin<sup>1</sup>, Richard Haslam<sup>2</sup>, Cedric John<sup>3</sup>

<sup>1</sup>Department of Earth Sciences, Durham University, UK

<sup>2</sup>British Geological Survey, Keyworth, UK

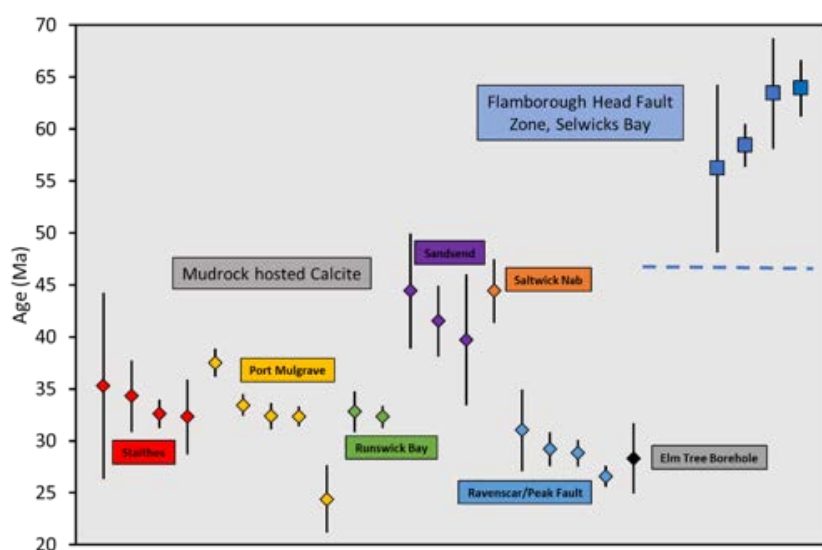
<sup>3</sup>Department of Earth Science & Engineering, Imperial College London, UK

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Organic-rich mudrocks are of great significance to the petroleum industry and for future Carbon Capture and Storage. Mudrocks act as top seals, source rocks and/or unconventional reservoirs and natural fractures within mudrocks can strongly influence top seal integrity, primary migration and the performance of unconventional (e.g. shale gas) reservoirs. This project studies the exhumed, early-mature, Jurassic mudrock succession of the Cleveland Basin, NE England, combining structural geology with isotope geochemistry and geochronology. The primary objective is to provide an absolute chronology of faulting and fracturing through novel U-Pb geochronology of fracture-fill calcite. The abundance of well-exposed, natural fractures with different orientations and failure modes provides an opportunity to investigate the properties of these fractures, and provide a basin-wide temporal and spatial framework of evolving deformation. The second objective is to use trace element, stable isotope, and clumped isotope analyses, to constrain fluid composition and temperature. In combination, these objectives will provide an integrated understanding of fracturing, faulting and fluid migration during burial and exhumation of a sedimentary basin.

The current results (Figure 1) provide intriguing insights into the history of the Cleveland Basin. The E-W trending Flamborough Head Fault Zone (FHFZ) bounds the basin to the south, and calcite preserved in one of the major extensional faults provides ages of 65-56 Ma. Calcite from N-S to NNW-SSE trending normal faults and associated fractures in the north of the Cleveland Basin provide ages of 44-24 Ma, revealing a previously unknown phase of Cenozoic faulting, which we speculatively relate to salt-related deformation. Structural and petrographic information suggest that the E-W and N-S trending faults have contrasting fracture-fluid-flow systems. Large (up to 30 cm), chalk hosted, vuggy calcite cements with geopetal sediment-fills in the E-W fault zone suggest it acted as an open fluid conduit with voluminous fluid-flow, linking the shallow sub-surface with deeper levels of the stratigraphy. In contrast, typically thin (<5 mm) vein fills with varying crack-seal-slip type textures in the N-S mudstone-hosted fractures of the Cleveland Basin provide evidence of episodic slip of variable displacement; these fracture openings may partly be controlled by pore fluid pressures. Ongoing structural and microstructural analyses, combined with trace element and

stable isotope tracing of fluid sources, will allow the testing of these initial hypotheses.



*Current calcite U-Pb geochronology results. Two distinct phases of calcite mineralization are shown:*

1. E-W Flamborough Head Fault Zone (Chalk hosted) – 64-56 Ma.
2. N-S Cleveland Basin faults/fractures (Mudrock hosted) – 44-24 Ma.

## **Techniques to validate subsurface interpretation for folds and fold-thrust related geometries using examples from coalmine dataset in lower Rhine basin - Ruhr sub-basin, Germany:**

***Ramy Abdallah, Prof Rob Butler and Dr Clare Bond;***

Ruhr sub-basin is geologically famous by coal-bearing layers as mining exploration fields from the late Carboniferous age. The structural genesis and tectonic evolution history of the late Carboniferous foreland Ruhr sub-basin related to Variscan orogeny. The deformation of the sub-basin is represented by the consistent folding of Carboniferous coal multi-layers. The structures of the sub-basin represent an isolated disconnected fault thrust model and a disharmonic folding regime which make the dataset ideal to analyse fold and fold-thrust geometries in multi-layered stratigraphy.

Conventional structural interpretation techniques for identifying the subsurface folds and fold-thrust geometries are challenged by limited data quality, complex structures, computational inefficiency and/or biased human factors by adopting a narrow range of idealized geometries. Idealized models along with simple outcrops which represent the end members or type models' examples are regularly utilized when constructing subsurface fold-thrust geometries. This method, common through academia and in the oil and gas industry, results in interpretation bias and can lead to poor commercial outcomes. Several drilling failures in thrust belts result from over-optimistic structural risks analysis. This presentation aims to reduce these risks by using interpretation validation techniques in folds and fold-thrust related geometries using coalmines dataset from the Ruhr sub-basin.

The fantastic subsurface control provided by galleries, and shafts created for deep coal-mining - make the dataset perfect to investigate fold and fold-thrust geometries in multi-layered stratigraphy. The main challenge is to use these datasets to create viable cross-sections and later to test these interpretations using displacement-distance profiles. The greater ambition of the study is to develop consistent interpretation protocols that can be applied to other high-resolution subsurface datasets including other parts of the lower Rhine basin in Aachen-Erelenzer and Sudlimburger-Steinkohlenreviers coalfield regions, North-western part of Germany.

Herein, displacement-distance techniques have been tested on the Ruhr sub-basin coalmine fields dataset. Displacement-profiles can help to identify faults tips, analysis folds geometries and relation between horizons and faults. Displacement-distance plots of an idealised model for isolated single faults is at a maximum near the centre and diminishes outwards in all directions to the edge of the fault, the tip-line, where the displacement is zero. The plots of the idealised model show a smooth normal distribution. However, fold-thrust displacement profiles of Ruhr coalmine dataset show variations from the normal distribution by increase or decrease of displacement. This can be attributed to either the mechanical stratigraphy of the layers. Or the initiation of a branch or splay fault or folding where the displacement transfers partially to a different structure. Or wrong interpretation where the relation between faults and horizons misinterpreted resulting in abnormal fold-thrust geometries and displacement distribution. By plotting and analysing the displacement profiles we can challenge, improved and better understand our fold-thrust geometries. Nevertheless, in the conventional interpretation workflow interpretation validation is not utilised. Moreover, the long term aim of the study is to better understand the range of possible geometries and maximise the use of the available data, creating features vectors to enhance the prediction of the fold geometries by applying data mining and machine learning approaches.

## **Fracture distribution within a carbonate hosted relay ramp: insights from the Tre Monti fault (Central Italy)**

By Mercuri, M., Carminati, E., Tartarello, M.C., Brandano, M., Mazzanti, P., Brunetti, A., McCaffrey, K.J.W., and Collettini, C.

Fracture distribution controls fluids circulation in fault damage zones, with evident implications for fault mechanics, hydrogeology and hydrocarbon exploration. Being usually characterized by a strong damage and structural complexity, this is of particularly importance for relay zones. We investigated the fracture distribution within a portion of a relay ramp damage zone pertaining to the Tre Monti fault (Central Italy). The damage zone is hosted within peritidal carbonates and located at the footwall of the relay ramp front segment. We analysed the distribution of the fracture density in the outcrop adopting a multidisciplinary study, involving classical and modern structural geology techniques: (1) scanlines measured in the field, (2) oriented rock samples, and (3) scan-areas performed on a virtual outcrop model obtained by aerial structure from motion. Scanlines and virtual scan-areas show that fracture density increases with the distance from the front segment of the relay ramp. Moreover, all the methods highlight that supratidal and intertidal carbonate facies exhibit higher fracture density than subtidal limestones. This trend of fracture density has two main explanations. (1) The damage is associated with the relay ramp development. Approaching the centre of the relay ramp (i.e., moving away from the front segment) an increase in the number of subsidiary faults with their associated damage zones produces high fracture densities. (2) The increase in fracture density can be attributed to the increasing content in supratidal and intertidal carbonate facies that are more abundant in the centre of the relay ramp. Our results highlight structural and lithological control on fracture distribution within relay ramps hosted in shallow water limestones.

## **Salt-carbonate interactions on the West Central Shelf, offshore UK**

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Salt tectonics, and especially the growth of diapirs, is typically thought to be driven by the flow of mobile evaporites such as halite and potash salts. This is especially true towards the deep, halite-rich centres of many ancient salt basins, where post-depositional salt mobilisation is commonly driven by loading of salt by overlying, denser sediments. This situation is considerably more complex towards the margins of salt basins, where non-evaporitic strata, such as carbonates and clastics, may be deposited at the same time as the more mobile, evaporitic strata. In these settings, salt can be mobilised whilst it is being deposited, leading to complex structural styles. Salt-carbonate interactions have been documented in the Zechstein Supergroup (ZSG) (Upper Permian) of NW Europe. Here, the basin margins and intra-basin highs are dominated mainly by immobile carbonate and anhydrite sequences, whereas the deeper basin is richer in halite that flowed to create salt stocks and walls. The Devil's Hole High is a prominent intra-basin high located on the West Central Shelf, offshore UK. This structure is thought to be capped by a carbonate-rich ZSG succession, with previous studies showing that flanking areas being characterised by intra- (rather than post-) ZSG minibasins caused by gravity gliding of the salt towards the deep basin, despite containing relatively low amounts of halite. The carbonate minibasins sunk down into the lower halite due to their excess density. We use 3D seismic reflection data to better understand these intra-ZSG salt tectonics features. Detailed mapping suggests the interaction between the different intra-ZSG facies is more complicated than previously believed. We observe inclined reflections within the inferred carbonates, dipping away from the flanks of salt walls; these may represent clinoforms within carbonate bodies that prograded away from the lower mobile, diapiric salt. By studying the complexity of salt-carbonate interactions in the West Central Shelf, Central North Sea, we can potentially improve our understanding of the intra-Zechstein hydrocarbon play in the North Sea, as well as other salt-related plays. From these data we can also generate better generic models for evaporite-carbonate interactions.

In theory, pockets of fluid in brittle media can be transported large distances, provided that both the fluid volume is large enough, such that fluid pressures can fracture the rock, and that stress gradients exist causing asymmetric growth of the fracture's front. Currently, industrial injections are deemed safe based on empirical observations of volumes, rates and pressures from closed-access industrial data. Existing theoretical models are difficult to use *a priori* to predict the critical volume of fluid that will cause unhindered fracture ascent, as they are expressed in terms of the fracture's length, which is hard to predict *a priori* and difficult to measure. Here we constrain scale-independent critical volumes as a function of only rock and fluid properties by supplementing simple analytical models with numerical simulations in three dimensions. We apply our model to laboratory and natural settings, showing that the volumes we estimate match well with laboratory data and can be used as a conservative estimate in geological applications.

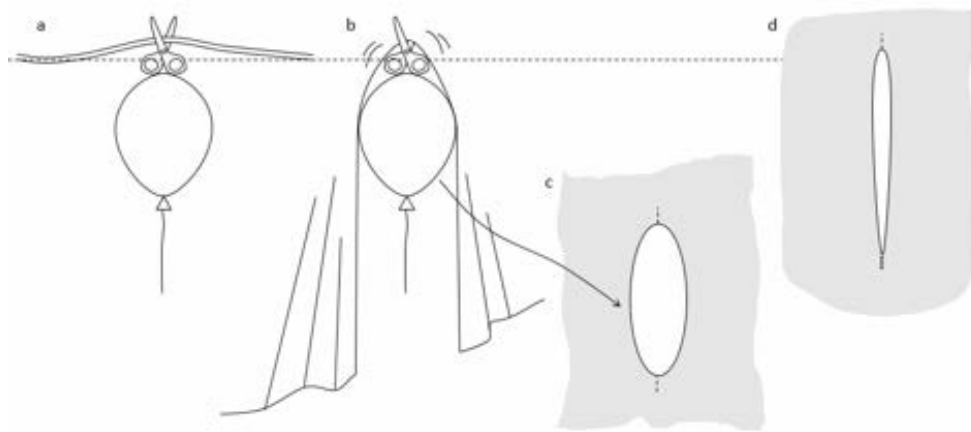


Figure: theoretical though experiment for vertically ascending fractures.



Figure: Fracture ascent modelled numerically, colour scale is  $K_{IC}$  divided by the fracture toughness of the host rock.

# Onshore evidence for oblique reactivation of the pre-existing Devonian structures as an insight into the Mesozoic opening of the Inner Moray Firth Basin

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Keywords: fault reactivation, onshore analogues, hydrocarbon play

New detailed field observations augmented with drone photography and creation of 3D digital outcrops of the Old Red Sandstone strata bordering the onshore Inner Moray Firth Basin have been used to explore the role of inherited Devonian faults in basin development during the Mesozoic-Cenozoic. The potential influence of older structures related to the Orcadian Basin on the kinematics of later basin opening has received little attention, partly due to the poor resolution of seismic reflection data at depth as well as sparse well data. Onshore studies have revealed sub-seismic structural styles providing a structural template for interpretation of the subsurface. They've also provided new information concerning the earlier kinematic history of the basin and better constraints on the influence of reactivation which ultimately leads to reductions in subsurface uncertainties.

Key fieldwork findings include dip-slip (Fig. 1c) N-S to NE-SW striking Devonian faults, some of which are demonstrably syn-sedimentary, related to the opening of the Orcadian Basin. These trends show evidence of later dextral reactivation (Fig. 1a, d) during NW-SE extension, with sinistral WNW-ESE to NW-SE striking faults and folding developed at the same time. The folds are open and plunge gently NW. They become tighter, moderately plunging (40°) and hinge lines rotate towards N-S, close to major dextrally reactivated faults (Fig. 1b). This later deformation is consistently associated with calcite mineralization (e.g. slickenfibers, Fig. 1d). New U-Pb dating of syn-kinematic calcite veins shows that the age of faulting associated with calcite mineralization is  $153 \pm 0.68$  Ma (Upper Jurassic).

This holistic approach confirms that widespread oblique Jurassic reactivation of earlier Orcadian Basin structures occurred. This reactivation created sub-seismic structural heterogeneity in potential Devonian reservoirs. An integration of fieldwork findings with subsurface interpretations can unlock the full potential of this area and should significantly enhance future offshore exploration.

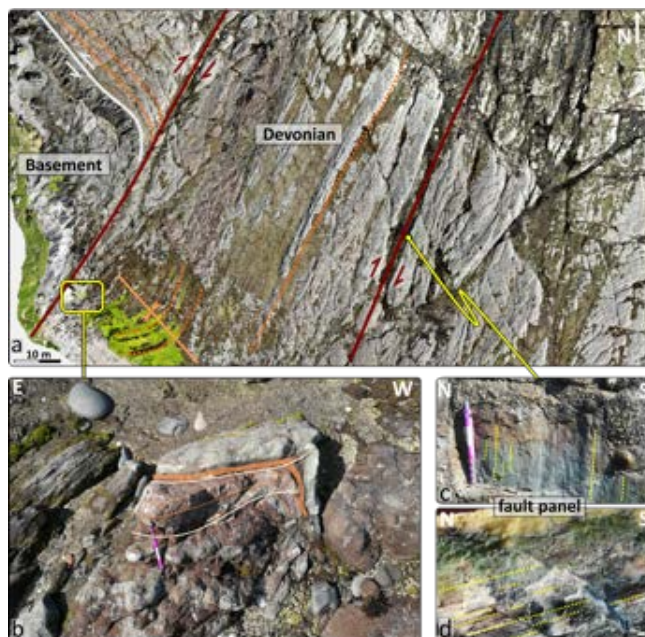


Figure 1. Examples of faulting and associated structures cross-cutting Devonian sandstones (New Aberdour Bay, southern coast of Moray Firth). a) Top view orthomosaic obtained from UAV (Unmanned Aerial Vehicle) photography, using Agisoft Metashape Pro, illustrating dextral reactivated NE-SW striking faults (red), sinistral NW-SE striking faults (white) and gentle to b) tight folds. Bedding is highlighted in orange. Fault panel showing c) early dip-slip slickenlines and d) overprinting oblique-dextral calcite slickenfibers.

## The nature and origin of structures within the Burren, County Clare, Ireland.

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### Abstract

The structure of Carboniferous limestones of the Burren area in County Clare is relatively simple compared to that of adjacent areas and much of Ireland. Very gentle folding and the paucity of faulting has generally been explained by one of two models invoking the presence of: (i) a major NNE-oriented shear zone, the Fergus Shear Zone, separating the Burren from the central part of Ireland to the east or (ii) a N-S oriented ramp of the main Variscan decollement which overlies the Burren sequence and cuts stratigraphically downwards towards the east. In this study we investigate the origin of associated structural differences between the Burren and elsewhere, and we examine an array of hydraulic fractures that are widely developed within the Carboniferous rocks of Ireland but are superbly exposed and best studied within the otherwise relatively undeformed Burren sequence.

Our analysis of the geometry and kinematics of lower Carboniferous normal faulting and later Variscan deformation from seismic, well and outcrop data, indicates that any spatial variations in complexity are apparent and can instead be attributed to temporal changes in structural evolution. This conclusion is supported by evidence highlighting the post-rift nature of the Burren sequence, with the main links between syn- and post-rift structure restricted to: (i) monoclinical folding above syn-rift inverted normal faults and (ii) an array of N-S trending calcite-dominated hydraulic fractures and veins (1µm to 50cm thick) attributed to the valving of overpressured fluids within Lower Carboniferous basins during N-S Variscan compression. Lateral continuation of normal faults under the post-rift Burren, without an intervening shear zone or decollement ramp, is supported by the geometry of monoclinical folds and by the spatial distribution of sulphide-bearing (mainly galena and sphalerite) veins that may have been scavenged from underlying Lower Carboniferous hydrothermal Zn-Pb mineralisation equivalent to the classic Irish-type Zn-Pb deposits developed directly along strike to the east.

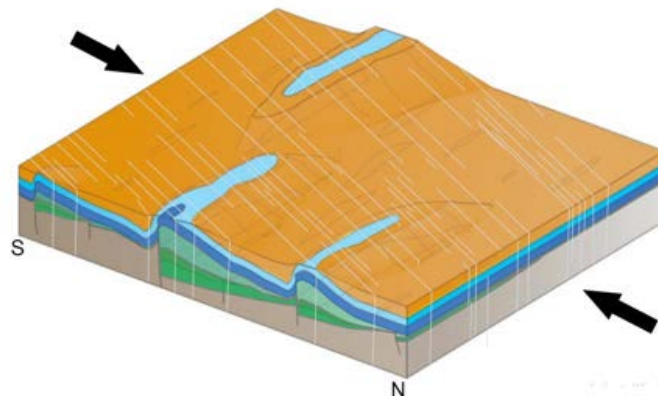


Figure 1: Schematic diagram of the structure of the Burren area, Co. Clare (Walsh et al. in press, Irish Journal of Earth Sciences).

# The propagation direction of slip increments on ancient normal faults

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The lack of an unambiguous method for determining the propagation direction of slip events on faults over significant time periods limits our understanding of the long-term stability of fault slip propagation directions. A geological means for determining the propagation direction of slip events during the growth of faults is provided by mutually cross-cutting faults and bed-parallel slip-surfaces in the Ptolemais Basin, northern Greece.

In the Kardias lignite mine, Ptolemais Basin, bed-parallel slip surfaces intermittently offset Quaternary faults as they grew, to form discontinuities on otherwise continuous fault surfaces. Subsequent fault slip increments bypassed these discontinuities to re-establish a continuous fault trace and leave an associated ‘dead’ splay (Fig. 1). The geometry and displacement distributions at these fault/bed-parallel slip intersections record the fault displacement at the time of bed-parallel slip and whether the next fault slip increment had an upwards or downwards component to its local propagation vector.

A database (N = 88) of slip propagation directions and fault throws was derived from continuous mapping of mine faces during lignite extraction over an eight year period. The data demonstrate a clear relationship between slip propagation direction and the accumulation of fault displacement on individual faults. During the early stages of fault growth, slip events propagated almost exclusively upwards through the mined sequence, but later stages of growth are marked by slip events showing both upward and downward components of propagation. The data therefore demonstrate that the location of the point of initiation of fault slip events on these Quaternary faults varied over the fault surfaces as the faults grew.

The emergence of systematic results from our analyses suggests that cross-cutting relationships between other synchronously active structures (e.g. conjugate faults) can provide a robust means for determining the propagation directions of slip events on ancient faults at outcrop.

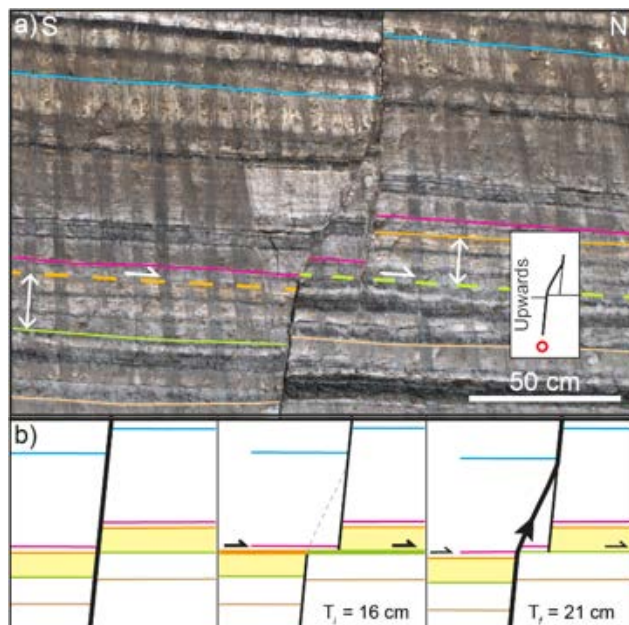


Fig. 1. (a) Outcrop photograph of a normal fault that downthrows to the left with a throw of 21 cm. (b) Stages in the development of the fault geometry in (a). The area shaded yellow is cut-out by a top to the north bed-parallel slip surface (half arrows). The missing section is equal to the throw at the time of bed parallel slip and is indicated by the double-headed arrows in (a). Full arrow in (b) indicates the propagation direction of the first slip event following bed-parallel slip offset of the fault.

## **The interplay between deformation and metamorphism in lawsonite eclogites from the Yukon-Tanana Terrane, Yukon Territory, Canada and implications for rheological behaviour during subduction and exhumation**

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Exhumed high-pressure metamorphic rocks, particularly those that preserve a history of deformation, offer a unique window into the processes that occur in subduction zones at depth. Understanding deformation in eclogites is integral to understanding rheological behaviour during subduction and exhumation. Metamorphism and deformation often go hand in hand, and mineral growth, chemical zoning and/or mineral transitions may result from enhanced or inhibited chemical transport during transient permeability facilitated by deformation. Conversely, mineral phase transitions can have a strong influence on rheological behaviour. Generally, the timing of deformation preserved in eclogites is also unclear, i.e. are preserved fabrics formed during subduction or during exhumation? Or do the rocks preserve a continuous deformation history along the entire P-T path? By using electron backscatter diffraction (EBSD) data together with element mapping and phase equilibrium modelling some of these aspects can be examined.

Using these techniques, we describe Cordilleran lawsonite eclogites from Faro in the Yukon-Tanana Terrane, Yukon Territory, Canada that experienced peak metamorphism at 490 – 580 °C and 1.9 – 2.2 GPa. The eclogites formed during Permian subduction in the Slide Mountain Ocean, a small ocean off the west coast of Palaeo-North America. Closure of this ocean resulted in collision between the Yukon-Tanana continental island arc and the western edge of Palaeo-North America. We discuss the evolution of the eclogites considering the relationships between crystal plastic deformation, crystal growth and metamorphic reactions. We differentiate between fabrics developed at different stages along the P-T path, describing a long-lived subduction and exhumation history. We present fabrics and mineral reactions that record a potential switch from subduction to exhumation, and we discuss the implications for the associated deformation processes and rheologic behaviour in subduction zones. We also discuss the larger scale tectonic implications for this early Cordilleran ocean closure event.

## **Fault core architecture and evolution in basalts: implications for mechanical and fluid-mediated weakening**

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Faults constitute a major source for mechanical and permeability heterogeneity in basaltic sequences, yet their architecture, and mechanical and physical properties remain poorly understood. These factors are, however, critical as basaltic reservoirs become increasingly important for geothermal applications and CO<sub>2</sub> storage. Here we present a detailed microstructural- to outcrop-scale characterisation of mature (decametre-hectometre displacement) fault zones in layered basalts in the Faroe Islands. Outcrop scale structures and fault rock distribution within the fault zone were mapped in the field to build 3D virtual outcrop models, with detailed characterisation of fault rock microstructure obtained from optical and SE-microscopy.

The fault zones record progressive localisation from decametre-wide shear zones in which deformation is accommodated by Riedel shear sets, which evolve to metre-wide fault cores with distributed internal shear, through shear plane locking and stepping of cataclastic bands. Deformation mechanisms in the core alternate between shear with compaction, evidenced by foliated cataclasite and gouge development, and dilatation through fluid overpressure, leading to hydrofracture and vein formation. Generally, a decametre wide damage zone of precursor Riedel faults is centrally transected by the fault core. The Riedel sets are highly localised, sigmoidal and preferably develop as R shears and subordinate P shears. The fault core is organised around a principal slip surface (PSS) hosted in a decimetre wide principal slip zone (PSZ). The PSZ consists of highly mature (ultra-) cataclasites with a zeolite matrix and varying concentrations of smectite. The transition from PSZ to damage zone occurs either as an immediate shear strain boundary with undeformed and unaltered host rock, or as a more gradual transition through lenticular low strain zones bounded by anastomosing high strain cataclastic bands. Low strain zones and cataclastic bands are distinguished by their degree of comminution and chemical alteration. PSS-proximal zones usually show significant late stage dilatation in the form of hydrothermal breccias or tabular veins with up to decimetre apertures, filled with early syntaxial to blocky zeolite and/or late coarse ( $\leq 1$  cm) blocky calcite. The described structures can be found overprinting each other, evidencing a pulsed fault activity and potentially migration of the PSS over time. The alternating deformation styles – shear-compaction and dilatation – suggest changes in deformation mechanism that may be linked to transient permeability decrease within the PSZ, followed by fluid pressure build-up, overpressure, and hydrofracture. Overall rock mechanical properties are thus governed by the combined effects of permanent chemical weakening and transient fluid-mediated mechanical weakening, alternating with cementation and healing, and will be explored by direct shear deformation experiments in the future.

# Geomorphic expressions of collision tectonics in the Qilian Shan, North Eastern Tibetan Plateau

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The Qilian Shan, North Eastern Tibetan Plateau, is an area of active deformation, caused by the India-Eurasia collision. We use geomorphic indices to highlight variations in the landscape across the Qilian Shan. Geomorphic indices reflect the spatial distribution of erosion in the landscape and the landscape's response to competition between tectonics and climate. We use the geomorphic indices of hypsometric index (HI), normalised channel steepness ( $K_{sn}$ ), elevation-relief ratio (ruggedness, ZR) and surface roughness (SR).

Thrust faults in the area broadly trend NW-SE. In areas where rivers flow across these thrust faults high HI,  $K_{sn}$  and low ZR occur in the hanging walls, consistent with active uplift of these structures. Relatively high HI ( $> 0.15$ ) and  $K_{sn}$  ( $> 100$ ) values occur in the Eastern region. Rivers in this region flow parallel to the thrust faulting and the high values here are therefore attributed to the difference between longitudinal drainage systems excavating broad zones between thrusts and the narrow, focussed networks of axial rivers crossing areas of active uplift. Drainage isolation has caused the central region, around Lake Hala and Lake Qinghai, to become flatter than range margin areas ( $K_{sn} < 50$ ,  $HI < 0.1$ ). The Western region shows localised high HI and  $K_{sn}$  values at the Altyn Tagh Fault. Higher HI values occur in the East, West and North parts of the range, with the location of the boundaries largely controlled by strike slip faults. The East-West precipitation gradient across the Qilian Shan of  $>500$  mm/yr to  $<100$  mm/yr is not a first order control on the regional landscape.

There is an abrupt northwards transition from low to high HI,  $K_{sn}$  and SR and high to low ZR partially coincident with the left-lateral Haiyuan Fault. A south-to-north transition from creeping to locked behaviour on an underlying detachment thrust has previously been suggested to occur along the intersection of this thrust detachment with the overlying Haiyuan Fault, thereby providing a potential explanation for the location of the geomorphic change. Our results show how the landscape in the area is sensitive to the underlying tectonic structure, pointing the way for future studies of regional geomorphology as a tool for understanding tectonics.

## **Diachronous Tibetan Plateau landscape evolution derived from lava field geomorphology**

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Evolution of the Tibetan Plateau is important for understanding continental tectonics because of its exceptional elevation (~5 km above sea level) and crustal thickness (~70 km). Patterns of long-term landscape evolution can constrain tectonic processes, but have been hard to quantify, in contrast to established datasets for strain, exhumation and paleo-elevation. This study analyses the relief of the bases and tops of 17 Cenozoic lava fields on the central and northern Tibetan Plateau. Analyzed fields have typical lateral dimensions of 10s of km, and so have an appropriate scale for interpreting tectonic geomorphology. Fourteen of the fields have not been deformed since eruption. One field is cut by normal faults; two others are gently folded with limb dips <6°. Relief of the bases and tops of the fields is comparable to modern, internally-drained, parts of the plateau, and distinctly lower than externally-drained regions. The lavas preserve a record of underlying low relief bedrock landscapes at the time they were erupted, which have undergone little change since. There is an overlap in each area between younger published low-temperature thermochronology ages and the oldest eruption in each area, here interpreted as the transition between the end of significant (>3 km) exhumation and plateau landscape development. This diachronous process took place between ~32.5° - ~36.5° N between ~40 and ~10 Ma, advancing northwards at a long-term rate of ~15 km/Myr. Results are consistent with incremental northwards growth of the plateau, rather than a stepwise evolution or synchronous uplift.

This paper is in press for *Geology*, with an expected publication date of February 2020.

# **Tectonic evolution of Anglesey and adjacent mainland North Wales: accretion of peri-Gondwanan elements in the UK sector of Iapetus**

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## **Abstract:**

The Appalachian-Caledonian Orogen preserves a complex record of piecemeal trans-oceanic terrane transfer, rotation, and accretion during the Lower Palaeozoic collision between West Gondwana and Laurentia. The intervening Iapetus oceanic tracts were very largely destroyed. The now preserved terranes include arc fragments of Laurentian and Gondwanan affinity, oceanic fragments incorporated into the Gondwanan continental margin (West Avalonia *s.s.*), and remnants of the Gondwanan continental slope apron and adjacent platform (representing both Ganderia and Megumia).

A century after Edward Greenly's original mapping of Anglesey was published by the Geological Survey, we present a new tectono-stratigraphic synthesis for the island of Anglesey and adjacent parts of NW Wales (and announce a new 2020 edition of the geological map!). That synthesis reveals a comprehensive record of the Appalachian Wilson Cycle on the UK segment of the orogen of the peri-Gondwanan margin, prior to highly oblique amalgamation into the Laurentian margin. We identify elements of Late Neoproterozoic accretion forming the pre-Appalachian basement; Cambrian extension, deposition and continental margin growth; Early Ordovician accretion and renewed extension; transfer and rotation across Iapetus; and finally, terminal Caledonian collision and continental foreland basin development.

**Numerical investigation of continental extension in heterogeneous cratonic lithosphere,  
constrained by observations from the Labrador Sea  
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Lithospheric extension, controlling the evolution of rifted margins, is governed by the interplay between the forces exerted on the plate boundaries and the rheological stratification of the lithosphere. The latter is a function of composition and thermal structure, which are strongly influenced by lithospheric inheritance. This relationship is well illustrated in the Labrador Sea, where rifting took place in cratonic lithosphere formed by the assembly of three distinct Precambrian tectonic units. Each unit exhibits distinct pre-rift lithospheric layering and thermal structure. Present-day observations from the Labrador Sea indicate that rifting and continental break-up resulted in a segmented margin with along-strike changes in the rift evolution, the crustal architecture, and the timing and magmatic budget of continental breakup.

In this study, we examined the effects of inherited lateral variations in the rheology of a cratonic lithosphere on rift evolution and margin architecture. To this purpose, we used numerical modelling constrained by observations from the Labrador Sea. The results of our 2D and 3D thermo-mechanical experiments demonstrate that in cratonic setting, where the lithosphere is relatively cold, variation in heat flow have a reduced impact on the evolution of rifting. Whereas, composition and thickness of the lithospheric layers appear to control the architecture of the margin, its asymmetry, the amount of hyper-extension, and the nature of the continental-ocean transition. Using plastic and/or viscous weakening, we show that the viscous flow in the lower crust delays continental breakup by promoting rift migration, crustal hyper-extension, and mantle exhumation.

## Hydrogen storage and faults: learning from natural analogues

*Christopher J. McMahon, Dr Katriona Edlmann, Dr Jennifer J. Roberts, Dr Gareth Johnson, Prof Zoe K. Shipton*

The potential role of hydrogen in achieving a net zero emissions future is gaining traction. A hydrogen economy would likely be supported by geological formations in which to store hydrogen at times of excess and to extract in times of demand, akin to subsurface natural gas storage.

Hydrogen can be generated through several subsurface processes: (a) hydrothermal alteration of ultramafic rocks (serpentinization), (b) radiolysis of water, (c), bacterial activity, (d) decomposition of hydrocarbons, (e) iron sulphide (pyrite) formation, and (f) mechano-radial processes. Therefore, hydrogen can be said to be a naturally occurring geofluid. Several naturally occurring hydrogen reservoirs and surface hydrogen seeps are documented worldwide. These hydrogen ‘plays’ could offer a low carbon energy resource, however this requires carbon accounting of the full chain process in comparison to other production methods. Further, hydrogen plays and hydrogen seeps offer opportunity to examine processes of geological containment of hydrogen.

It is well known that faults are significant for the fluid flow and trapping of crustal fluids, and studies of natural analogues for geological storage of CO<sub>2</sub> identifies faults as important leakage pathways. As with CCS, minimising the risk of hydrogen leakage is not only important to support the safety case for geological storage, but also to constrain risk of any economic losses from the migration of hydrogen from its intended storage formation. As such, deepening scientific understanding of the processes governing hydrogen containment and leakage is fundamental for: (a) prospecting of natural hydrogen plays, (b) informing effective site selection for geological hydrogen storage, and (c) the design and performance requirements of appropriate monitoring of these sites. It is useful to consider how learnings from oil and gas and CCS sectors might be translated and applied to hydrogen storage, accounting for differences in the physical and flow properties of the geofluids.

Here, we present a synthesis of the available literature on natural hydrogen accumulations and seeps, to examine commonalities and to identify knowledge gaps.

We find that while only one hydrogen accumulation is currently known in scientific literature, there may be others in existence or not reported. At this site, hydrogen accumulates differently to conventional hydrocarbons (e.g. methane), by accumulating in different strata and appearing to have different units which constitute a seal. This indicates that different parameters define a suitable source, reservoir and a seal/trap combination for hydrogen systems. There are few (5) known terrestrial examples of hydrogen seepage worldwide. In each case, the hydrogen derives from deep seated processes (e.g. serpentinization) rather than superficial bacteriological or other processes. Similar to observations at CO<sub>2</sub> seeps, sites of hydrogen seepage have a distinct surface expression in the form of a sub-circular depression which exhibit temporal variation (over yearly timescales), and the location, distribution and shape of these seeps are likely controlled by regional stress regimes and/or basement faults. Overall, we find very little is known about how hydrogen migrates and is trapped in the subsurface. Our work highlights the need for further research around the factors that govern hydrogen fluid flow, and thus the degree to which knowledge of fluid flow of other geofluids can be translated and applied to ensure effective and secure geological hydrogen storage.

# **Interactions of multi-scale fracture network within different sedimentological domain of an isolated carbonate platform at Latemar: implication for fluid-flow**

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Carbonate platforms accommodate pervasive multi-scale fracture networks in their deformed condition regardless of the scale of the deformation. These fracture networks exert major impact on the mechanical and flow behaviour in different sedimentological compositions of the platform bodies. A multi-scale fracture network arrangement in and around an isolated carbonate platform from Latemar – in the western Dolomites, northern Italy, is investigated focusing on characterizing geometry, patterns of stress fields, strain and different fracture interactions from the limestone lithofacies to their dolomitized equivalents. The interior of the Latemar carbonate platform presents an excellently exposed outcrop analogue for subsurface reservoirs of isolated carbonate build-ups affected by dolomitization and igneous activities. Here, we expand on the observed interaction between multi-scale fractures and fluid within the platform's different sedimentological domains i.e. limestone lithofacies and dolostones, using outcrop structural analysis, drone imagery and fluid-flow modelling.

The studied Middle Triassic Latemar platform is moderately deformed by the combination of a dense framework of high-angle mode I fractures (joints and veins), low-angle reverse conjugate faults, magmatic dikes and hybrid fractures. At the base of the platform, the low-angle reverse conjugate faults relate to sub-vertical stylolites and sub-horizontal joints that were formed in a stress field characterized by horizontal  $\sigma_1$  and vertical  $\sigma_3$ . Whereas the conjugate hybrid fractures, at the top of the platform, are associated with sub-vertical tectonic stylolites that were sustained in a stress field dominated by sub-horizontal  $\sigma_1$  and sub-vertical  $\sigma_2$ .

Results from the modelling suggest that fractures within the limestone and dolostone domains are correlated in terms of geometry and topology. These fractures act as the principal conduits for fluid-flow, and contribute to the dolomitization of the precursor limestone mostly when the fractures are open during the burial diagenesis. Numerical results further show that the geometrical and topological features of fractures including orientations, lengths, aperture and connectivity are critical in the preferred flow directions.

This study provides a robust analogue for hydrocarbon exploration and production from an isolated carbonate platform with limestone and dolostone reservoirs, particularly where these lithologies are intensely deformed with associated multi-scale fracture networks.

## **Plate driving forces: pushing plumes into the background**

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Observations of the apparent links between plate speeds and the global distribution of plate boundary types have led to the suggestion that subduction may provide the largest component in the balance of torques maintaining plate motions. This would imply that plate speeds should not exceed the sinking rates of slabs into the upper mantle. Instances of this ‘speed limit’ having been broken may thus hint at the existence of driving mechanisms additional to those resulting from plate boundary forces. The arrival and emplacement of the Deccan-Réunion mantle plume beneath the Indian-African plate boundary in the 67-62 Ma period has been discussed in terms of one such additional driving mechanism. Its spatial and temporal coincidence with an abrupt speed-up of the Indian plate has led to suggestions that the arrival of plumes at the base of the lithosphere can introduce a push force capable of overwhelming entire circuits of plates and triggering plate tectonic reorganizations.

We challenge the occurrence of a pulse of anticorrelating accelerations and decelerations in seafloor spreading rates around the African and Indian plates and, with it, the proposal that plume-related forces in the Indian Ocean had a significant impact on the Indo-Atlantic plate circuit in late Cretaceous and Paleogene times. Using existing and newly-calculated high-resolution models of plate motion, we show that the increase in spreading rates previously documented for ridges bordering the Indian plate is artefactual. Records from spreading centers throughout the Indo-Atlantic plate circuit show an ubiquitous increase in plate divergence rates at 67-64 Ma, which is best explained in terms of a timescale error affecting chrons 29-28. Corrected for this error, the motion of the circuit’s plates show little change around Deccan times. Furthermore, we find that Post-Deccan reorganization of the Indo-Atlantic plate circuit can be explained in terms of long-term plate boundary evolution without the need to invoke a large additional plume push force in the 70-60 Ma period.

## **Styles and scales of structural inheritance – Rifting across the Median Batholith Zone and adjacent terranes, Great South Basin, New Zealand**

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Continental crust is highly heterogeneous across multiple spatial scales. Different amalgamated and accreted tectonic units contain multiple heterogeneities reflecting their unique history, whilst the boundaries between these units may form crustal-to-lithospheric-scale structures. These different structural heterogeneities are able to influence different aspects of rift physiography across multiple scales simultaneously, yet the mechanics and styles of how they do so are often poorly understood.

Here, we use seismic reflection data to analyse the geometry and evolution of the Great South Basin, located offshore South Island of New Zealand. This basin is oriented perpendicular to the trend of the underlying basement terranes, including the Median Batholith Zone, a composite batholith comprised of multiple intrusive plutonic suites. At the largest whole-rift-scale, we show how the boundary between the Median Batholith and the adjacent, dominantly (meta-) sedimentary terranes of the Western Province was initially exploited by magmatism and then repeatedly reactivated forming a crustal-scale shear zone and associated upper crustal fault system. These structures are oriented perpendicular to and bisect the Great South Basin. Within the basin, we identify a series of stacked, likely granitic, laccoliths in crystalline basement expressed as sub-horizontal packages of high- and low-amplitude reflectivity, which we link to the youngest intrusive suite within the Median Batholith Zone. We find that the presence of this igneous material represents a relatively strong area of crust that inhibited fault nucleation, creating variable fault density across the rift. Further, we find that faults in the adjacent, relatively weaker crust splay and eventually terminate as they approach the stronger crustal block. Individual fault segments display kinematic and, for the most part, geometric coherence across the system; we suggest that the splaying is related to the boundary with the stronger crustal block dipping beneath the fault system. At the individual fault scale, we document multiple seismic fabrics within basement that show evidence for reactivation throughout the evolution of the basin and host multiple, low displacement faults. These low-displacement faults are pervasive across the area, but are most pronounced across the stronger area underpinned by the granitic laccoliths.

The Great South Basin illustrates a number of key general styles of structural inheritance, operating across multiple spatial scales, that may be applicable to rift systems globally: i) the reactivation of whole crust- to lithosphere-scale terrane boundaries; ii) the blocking of lateral fault propagation by areas of stronger crustal material; and iii) the reactivation of basement fabrics by small-scale faults. We show how these different styles of inheritance are able to influence different aspects of rift physiography, and offer insights into the mechanisms that govern them.

Fracture Network Characterization of the Culm Fold Zone, Western Harz Mountains – Germany,  
as a Means to Extract Geothermal Reservoir Parameters  
Katherine FORD, Bernd LEISS, Bianca WAGNER, Graciela SOSA

The focus of this study is to characterize an analogue site for the Variscan metasedimentary and metavolcanic Variscan basement, the potential target reservoir in an unconventional geological setting for the geothermal project of the University of Göttingen. The main outcome of which is to supply district heating for the entire campus. From interpolation of comparable units in the Rhenish Massif with the Harz Mountains, it is likely that the boundary that separates the Variscan autochthonous from the allochthonous zone is striking through the subsurface of the city area of Göttingen. For that reason the analogue site for this project has been chosen as the Western Harz Mountains, paired with the reasonable outcrop situation.

To understand and comprise the complex structural parameters that may be found in the expected alternating slate and greywacke units beneath the surface of Göttingen, a 3D conceptual structural model of the Variscan basement must be created as the first step. This contribution will focus on the interactions and changes of different structural parameters across the typical Variscan fold and thrust belt at outcrop scale. To accomplish this, intensive field campaigns and photogrammetry sessions are undertaken for detailed data collection on changes in parameters such as the fracture network, mineralization and lithology across the primary fold and thrust structure. The methodology presented focuses on the characterization of the fracture network through topological analysis. The main parameters defined within the study are connectivity, intensity and level of mineralisation. Then related to how these parameters change in various structural and lithological situations situated along the generalized fold and thrust structure, as a basis for understanding the complexity of the deformation exhibited in the Variscan Fold-and-Thrust belt.

Due to the complexity of the lithology and structures exposed in the Western Harz Mountains, a total of 29 outcrops have been categorized, and fracture trace maps have been collected at each defined category. As well as this, a 2.5D approach to fracture network characterisation has been undertaken. Trace maps are created on the bedding plane itself, and adjacent to the planes, this allows for the more holistic quantification of the fracture networks under varying exposure orientations and through the changes in lithology. This statistical approach to data collection will allow for a more generalised view of the interactions between the fracture networks and the lithological and structural framework, such as local-scale folds and faults, which for an analogue study is more suitable.

The preliminary results of this study do show a general trend of increased intensity, level of mineralisation and connectivity towards the fold hinge and thrust zone but are however more complex than this hypothesis. A much more detailed study must be undertaken to truly understand how fracture network characteristics are affected by changes in lithological and structural variations. With a detailed characterisation of the fracture network throughout this complex reservoir this is the first step in the creation of the conceptual structural model, following this with petrophysical and chemical parameterisation derived from lab experiments, reservoir models and EGS-exploitation strategies can then be developed and the reservoir potential realised.

# Extreme growth competition in veins: microstructures and models

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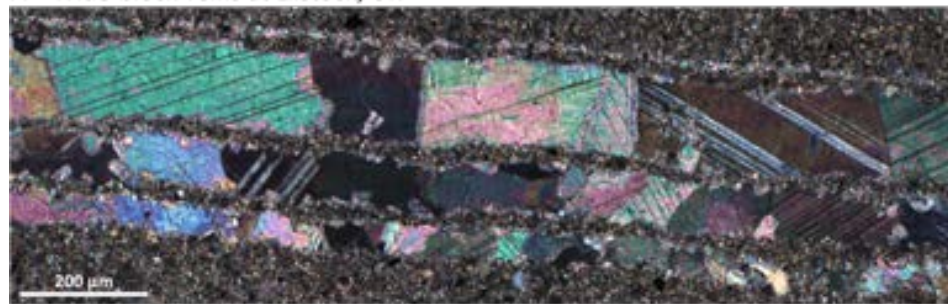
Microstructures of mineral veins contain a wealth of information on deformation kinetics, rock rheology, crystal growth and permeability evolution during tectonic events. Despite fundamental breakthroughs in understanding these microstructures, many questions regarding the controlling factors and dynamics of vein formation still remain.

In this contribution, we investigate the formation of syntaxial wide-block veins that are common in reservoir rocks worldwide but have been poorly understood. We combine a detailed microstructural investigation with phase field modeling to simulate the growth of calcite veins in a micritic limestone host from UK and Oman.

The results show that the studied veins grow in open fractures in a process that we refer to as an extreme growth competition. Syntaxial precipitation of vein cement is rapid on the broken surfaces of wall rock calcite that constitutes only ~10% of the fracture surface area. The rest of the fracture follows calcite grain boundaries that are coated by clay particles and thus inhibits the precipitation of the vein minerals.

With phase field models we demonstrate that a range of the observed microstructures in the natural samples can be obtained by varying the distribution of the “seed grains” and the initial opening aperture of the fracture. The results provide valuable insights in the dynamics of vein cementation and porosity evolution in carbonate reservoirs.

A Wide-block veins at Lilstock, UK



B Phase-field simulation

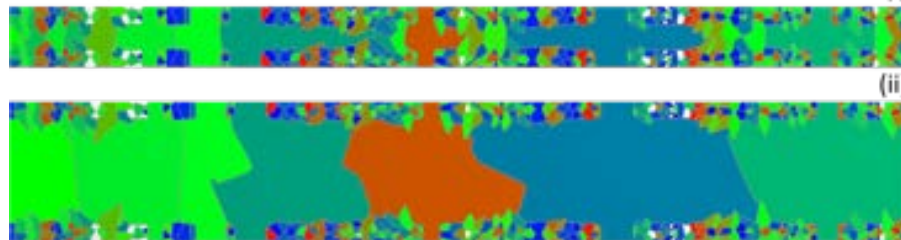


Figure 1. Microstructures of wide-block veins. A - natural calcite veins in Lilstock, UK showing the relationship between the grain width and vein thickness. B - Phase-field simulations, (i) - initial opening aperture is 2x the average host rock grain diameter; (ii) initial opening aperture is 8x the average host rock grain diameter. Different colours represent different calcite c-axis orientations in respect to the vein opening direction.

## **The temporal evolution of syn-sedimentary normal faults and the possible role of tip retreat**

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We need to understand how normal faults grow in order to better determine the tectono-stratigraphic evolution of rifts and the distribution and size of potentially hazardous earthquakes. The growth of normal faults is commonly described by two models: 1) the propagating fault model (isolated growth model), and 2) the constant-length model. The propagating fault model envisages a sympathetic increase between fault lengthening (L) and displacement (D), whereas the constant-length model states that faults reach their near-final length before accumulating significant displacement (Walsh et al., 2002). Several relatively recent studies agree that faults generally follow a constant-length model, or a “hybrid model” of the two, where most faults reach their near final length within the first 20-30% of their lives and accrue displacement throughout. Furthermore, in the past 20 years, much research has focused on how faults grow; relatively few studies have questioned what happens to the fault geometry as it becomes inactive, i.e. do faults abruptly die, or do they more gradually become inactive by so-called tip retreat. We here use a 3D seismic reflection dataset from the Exmouth Plateau, offshore Australia to support a hybrid fault growth model for normal faults, and to also determine the relationship between length and displacement as a fault dies. We show that the studied faults grew in three distinct stages: a lengthening stage (<30% of the faults life), a displacement accrual stage (30-75%), and a possible tip retreat stage (75%-end). This work has important implications in our understanding of the temporal evolution of normal faults, both how they grow and how they die.

# Dating faults, fractures, and fluids with U-Pb calcite geochronology (I): Strategies, progress, and pitfalls

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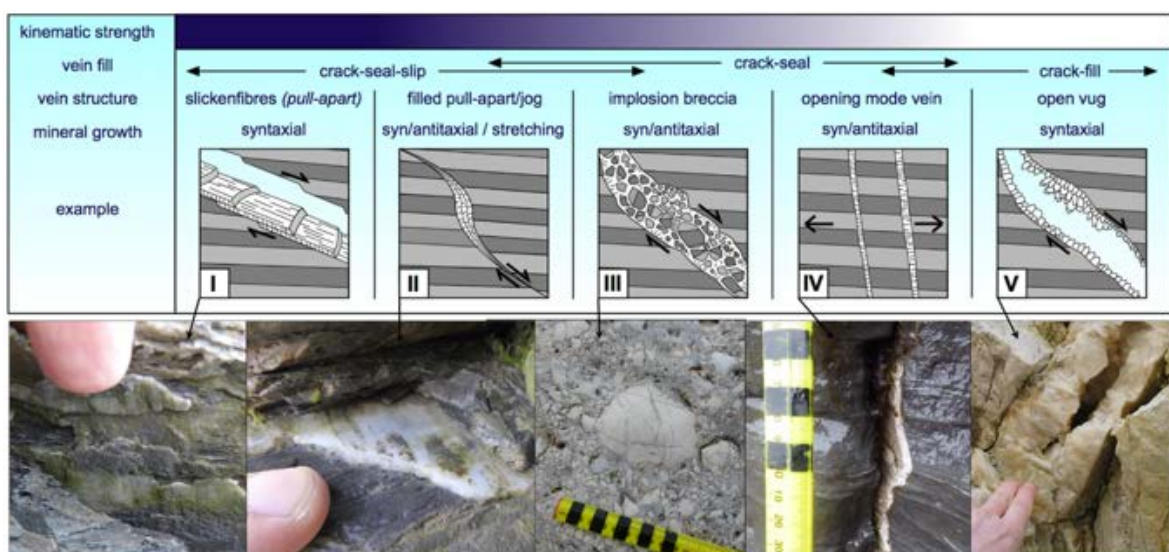
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Determining the timing of brittle deformation is critical in understanding how the upper crust behaves and deforms, but has long provided a significant challenge due to a lack of techniques that provide absolute age constraints, instead relying on relative and imprecise dating methods. In the last few years several methods have seen improvement and innovation, opening the doors for research in structural geology and tectonics to obtain new understanding through geochronology. These include K-Ar on illite, U-Th/He on hematite, and U-Pb/Th on calcite. The latter is the most commonly applicable, given the abundance of calcite mineralisation in fractures and fault planes in the upper crust. The *in situ* U-Pb method – laser ablation inductively coupled mass spectrometry (LA-ICP-MS) – has broadened the applicability of this technique to a wide range of geological settings. Here we present an overview of recent progress in this method, including strategies for obtaining dates of faults, fracture, and fluids, the common pitfalls and perils, and highlights for the tectonics community.

Strategies for obtaining and interpreting dates rely on the integration of microstructural, image-based, and compositional data. Linking dates to fault slip is not straightforward, and requires a good understanding of calcite growth mechanisms matched with field constraints (see below). Finding suitable material currently relies partly on luck, particularly regarding the abundance of uranium, but starting with good practise in the field and ending with ICP-MS can improve success rates. Settings the method has been applied to include: fold-and-thrust belt evolution, continental rift-related deformation, intra-plate fault reactivation, basin inversion, salt-related basin deformation, hydrocarbon migration, and fluid-flow in the crystalline crust.



Example vein types, with decreasing ability (left to right) to link dated calcite domains to fault-slip events.

## **Stretching transform faults in the Mediterranean region.**

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### **Abstract**

Faults that accommodate displacement rate discontinuities between regions deforming at different strain rates are called stretching faults, and can occur over a wide range of length scales in the Earth's upper crust. At the largest scale they form transform faults as a localization of deformation bounding a retreating segment of an earlier formed arcuate subduction zone. Finite displacements vary from zero at the fault tip to 100 km or more where they transform into the subducting segment. In the back arc region lithospheric stretching and thinning is marked by displacement rate vectors systematically increasing from zero at the fault tip region to the retreating subducting segment. Stretching transforms may act as boundaries between seismically active and relatively inactive crustal regions. The Mediterranean region presents three good examples of this behaviour: the Betic-Alborán region of S.E Spain and N. Africa, the Tyrrhenian-Calabrian region of S. Italy and Sicily, and the Aegean-Anatolian region of Greece and western Turkey.

Focussing on the Spanish example, the geodynamic setting has the internal Betic Cordilleras forming a wedge stretched during upper Miocene time behind the westward-retreating subduction zone comprising the Gibraltar Arc. Within the back-arc wedge, a complex of uplifted metamorphic basement complexes is separated by intramontane basins. The northern side of the wedge is formed by the right-lateral internal/external zone boundary and the Crevillente fault. On the southern side of the stretched wedge the Carboneras fault zone, together with the Palomares and Alhama de Murcia faults and faulting extending across the Alborán sea basin into Morocco form a soft-linked network of left-lateral stretching faults. They were active mainly between 13 and 6 Ma B.P, accumulating over 100 km of extension within the wedge, and accompanied by subduction-related volcanism, mainly in the Alborán sea. The Carboneras continental transform fault cuts and is intruded by these magmatic products.

The complex of uplifted basement blocks (Sierras Alhamilla and Cabrera) and the rocks of the Sorbas basin fill, lying immediately to the north of the Carboneras fault, demonstrate the dynamic linkage between the faulting and the effects of the adjacent lithospheric stretching. From a combination of (a) a gravity survey to reveal the shape of the basin floor, (b) detailed mapping to determine the geometry of the basin fill that presently takes the form of a westward-deepening trough and (c) petrophysical studies of the porous rocks of the basin fill, we show how the present 2 km of basin deposits is accommodated by low-angle extensional faulting off the uplifted basement blocks, leading to Tortonian age large-scale gravitational collapse of the freshly-deposited turbidite deposits. Upper Tortonian uplift and erosion led to the regionally important Messinian unconformity that has led to the older part of the basin fill being largely buried.

## **Local stress amplifications associated with viscous shear zone networks trigger lower crustal earthquake nucleation**

Lucy Campbell, Luca Menegon, Åke Fagereng and Giorgio Pennacchioni

Deep intracontinental earthquakes are still poorly understood, although they can cause significant destruction. Although the strength of the lower crust remains a topic of debate, dry lower continental crust is apparently strong at high-grade conditions. A strong rheology could potentially enable earthquake slip at high differential stress, even within a predominantly viscous regime, but this idea requires further documentation in the geological record. Here we analyse geological observations of seismic structures in exhumed lower crustal rocks. A granulite facies shear zone network dissects an anorthosite intrusion in Lofoten, northern Norway, with highly localised mylonitic shear zones separating relatively undeformed, microcracked blocks of anorthosite. In these blocks, pristine pseudotachylytes decorate fault sets that link adjacent or intersecting shear zones. These fossil seismogenic faults are rarely >15 m in length, yet record single-event displacements of tens of centimetres. This slip/length ratio implies large >1 GPa stress drops, indicating the high strength of the anorthosite blocks. These pseudotachylytes represent direct identification of earthquake nucleation in the lower crust and imply that transient seismicity helped maintain strain compatibility across the shear zone network during ongoing aseismic creep.

# **Reconciling geophysical and petrological estimates of the thermal structure of southern Tibet**

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## **Abstract**

The thermal structure of the Tibetan plateau – the largest orogenic system on Earth – remains largely unknown. Numerous avenues, both geophysical and petrological, provide fragmentary pressure/temperature information, both at the present, and on the evolution of the thermal structure over the recent past. However, these individual constraints have proven hard to reconcile with each other. Here, we show that models for the simple underthrusting of India beneath southern Tibet are capable of matching all available constraints on its thermal structure, both at the present day and since the Miocene. Many parameters in such models remain poorly constrained, and we explore the various trade-offs among the competing influences these parameters may have. However, three consistent features to such models emerge: (i) that present day geophysical observations require the presence of relatively cold underthrust Indian lithosphere beneath southern Tibet; (ii) that geochemical constraints require the removal of Indian mantle from beneath southern Tibet at some point during the early Miocene, although the mechanism of this removal, and whether it includes the removal of any crustal material is not constrained by our models; and (iii) that the combination of the southern extent of Miocene mantle-derived magmatism and the present-day geophysical structure and earthquake distribution of southern Tibet require that the time-averaged rate of underthrusting of India relative to central Tibet since the middle Miocene has been faster than it is at present.

# What controls igneous sill segmentation? Insights from the Exmouth Plateau, NW Shelf, Australia

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Magma typically moves large distances laterally and vertically through the crust via networks of dykes and sills. Over the last two decades, researchers have shown that the component intrusions within these networks do not always propagate as continuous sheets, but are rather segmented at their outer margins. However, the formation of elongated sill segments, as well as their connectors (i.e., steps, broken bridges) remain poorly understood. In this study, we present high-quality three-dimensional (3D) seismic reflection data from the NW Shelf, Australia, to infer potential emplacement mechanisms of fanning lobe networks that include elongate magma fingers, and to highlight the influence of pre-existing faults on magma flow pathways and sill morphologies. We also present quantitative measurements of segment connectors, which are structures that have important implications for identifying sill emplacement mechanisms, and that permit comparison between different seismic reflection datasets and the predictions of physical analogue models.

Our seismic data images five sills with different morphologies. In this study we focus on (1) a large inclined sheet and (2) an elongate saucer-shaped sill that intruded into a graben structure. The former intrusion formed a sub-horizontal, fanning lobe network at relatively shallow emplacement depths (~1100 m). We constrained the magma flow pathway by mapping intrusive connectors, which also highlight three orders of lobes with potential magma fingers emerging from the outer margin of third-order lobes. Measurements of segment-segment connectors show that the minimum vertical offset mostly occurs at the most inward part of the connectors, whereas the maximum vertical offset is approximately evenly distributed along the connector's length. Because stress rotation at propagating sill tips should result in minimum vertical separations that increase with increasing length along connectors, we can exclude stress rotation as a segmentation mechanism. The observed inconsistent stepping directions may indicate the exploitation of pre-existing weaknesses (e.g., bedding planes), which could have divided the sill into segments.

One sill in the Glencoe 3D survey was emplaced into a graben in which magma was injected parallel to and up the NNE-SSW-striking bounding faults, forming an elongate channel-like intrusion with inclined limbs. Where the sill is not bounded by the western fault, two sub-horizontal, semi-radially fanning lobe networks formed with an overall flow direction towards the WNW. Minor, linear-shaped amplitude variations at the outer margin are interpreted as thickness variations, potentially indicating coalesced magma fingers.

We conclude that sill morphologies in the Exmouth Plateau were likely influenced by: (1) the exploitation of pre-existing weaknesses (e.g., bedding planes), which potentially divided sills into segments; (2) variations in host rock lithology, which potentially led to non-brittle deformation and thus to magma finger formation; and (3) pre-existing structures where bounding fault planes led to an elongated channel-like geometry with inclined limbs.

# Linking deep-mantle structure with the bedrock record to test models of the India-Asia collision

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Advances in plate-reconstruction modelling allow geological and geophysical datasets to be readily integrated within a plate kinematic framework; this enables development of regional tectonic models that are consistent with the bedrock record, deep mantle structure and global tectonic plate networks. In this study, we evaluate the constraints that globally-consistent tectonic models for the India-Asia collision must satisfy. Particular focus is given to: (1) the reconstruction of subduction zones in the Neotethys Ocean; (2) the size of the Indian continent prior to collision; and (3) the distribution of subducted lithosphere in the upper and lower mantle beneath the India hemisphere determined by seismic tomography models. With these constraints, we evaluate three mutually exclusive models for the India-Asia collision: (1) the *single subduction model*; (2) the *double subduction model*; and (3) the *Greater India Basin hypothesis* (See figure below).

We use seismic tomography to identify slabs of oceanic lithosphere that have subducted into the upper and lower mantle. Correlation of this information with constraints from the bedrock geological record provides a means to test and develop paleogeographic and plate reconstruction models. By employing the assumption that a given slab sinks vertically within the mantle, it is possible to use the locations and geometry of subducted slabs to constrain paleo-trench locations in paleogeographic and tectonic plate reconstruction models. A vertical slab indicates that its paleo-trench remained stationary during subduction; a dipping slab indicates that its paleo-trench migrated laterally in the up-dip direction of the slab during subduction. The size and depth of a subducted slab can be related to the timing and duration of subduction. If the timing of subduction is known, then the depth of the slab can be converted into a sinking rate, which previous studies have estimated to be  $\sim 1.0$  cm/yr to  $\sim 1.5$  cm/yr. Thus, it is possible to use sinking rate estimates as an additional test of paleogeographic and plate reconstruction models. Using these concepts, slab geometries provide a robust constraint on the absolute location and timing of active paleo-subduction zones of the geological past.

Our synthesis of slab geometries and bedrock datasets within a plate kinematic framework reveals implicit assumptions inherent in each model for the India-Asia collision. Some of these assumptions challenge widely accepted geological or geodynamic concepts, including (1) our understanding of the geological record of suture zones in continental collisions; (2) the feasible limits of continental subduction; and (3) the rates at which lithospheric slabs sink in the mantle. We explore the implications of these challenges for our understanding of collisional zones, and discuss the remaining knowledge gaps related to the India-Asia collision and the process of continental collision in general.

## Tectonic stress controls igneous sill geometry.

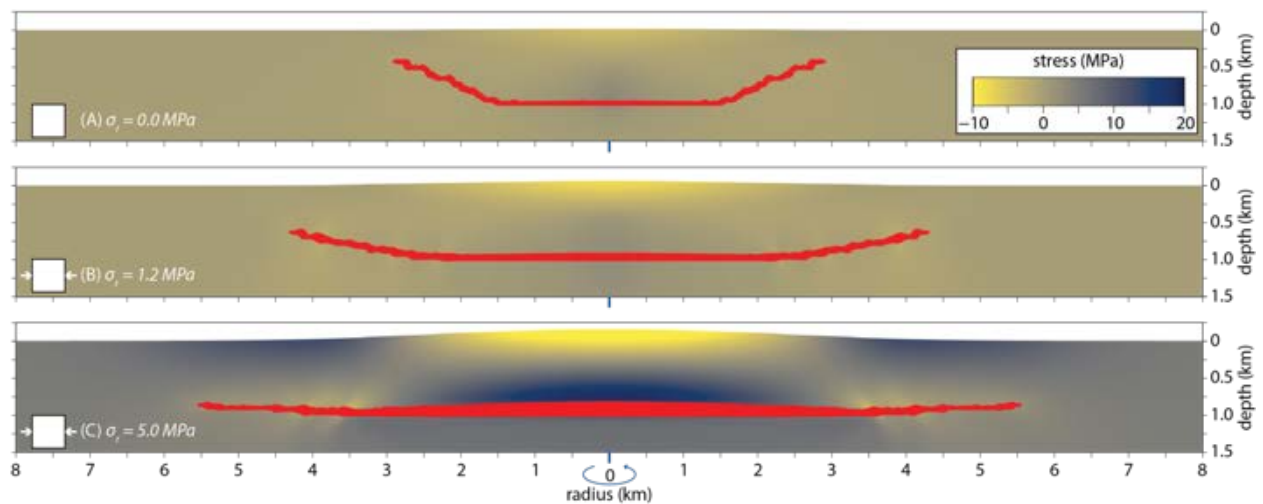
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Near-surface igneous sills commonly exhibit saucer-like shapes, formed due to interaction with the Earth's surface once some critical sill length,  $r_c$ , is reached relative to its depth. Sill geometry has been strongly linked to the host material conditions, particularly in terms of the elastic properties and shear cohesion of the host rock, operating as primary controls on sill geometry. Here we conduct dynamic numerical simulations for sill growth in the near surface, in which we vary the host rock properties, magma pressure profile internal to the sill  $\Delta P$ , and the externally applied tectonic stress  $\sigma_r$ , to consider their contributions to sill geometry. We find that elastic properties alone have little impact on sill geometry. The applied magma pressure profile in the models,  $\Delta P$  – here we consider the end member cases of (i) constant source pressure, and (ii) constant source flux – controls sill growth rate, but has little effect on overall geometry. In a constant source pressure model, sill growth rate increases exponentially as sill length increases. In a constant flux model, the increasing magma volume needed to maintain growth results in a slowing of the sill growth rate. Varied saucer-like shapes reflect the additive stress components of the magma overpressure within the sill, and the tectonic stress, controlled by the locus of the maximum energy release rate  $G_{max}$ . During initial sill growth,  $G_{max}$  is in-plane with the sill, but deflects to  $\sim 25^\circ$  at the critical base length  $r_c$  due to bending in the overburden. Increasing the horizontal tectonic stress  $\sigma_r$  subdues the effect of overburden bending, decreasing the incline angle, and increasing  $r_c$ . Host rock cohesion and elastic properties control the absolute magnitudes of  $\sigma_r$  required to affect a change in sill geometry.



*Igneous sills emplaced in an isotropic medium. The only variable in each model is the horizontal stress, which exceeds the lithostatic stress by (A) 0 MPa, (B) 1.2 MPa, and (C) 5 MPa.*

## **Basin structural analyses of Lower and Middle Benue Trough of Nigeria derived from the analysis of remote sensing, gravity and aeromagnetic data**

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### **Abstract:**

The Benue Trough is an intra-continental rifted basin located north of the Niger Delta where most of Nigeria's hydrocarbon reserves are found. Exploration of this area has been neglected over the years due to difficulties in geological and geophysical investigations owing to security concerns coupled with complex tectonic history covered by thick vegetation and sediment cover. We combined remote sensing, high-resolution aeromagnetic and land gravity data sets in mapping, and delineating, modelling and characterizing geologic structures within the basin. Remote sensing data were processed using directional and non-directional filters as well as shaded relief model transforms to enhance, trace and analyse concealed surface geologic structures. Gravity and aeromagnetic data sets were separated into apparent depth slices representing near-surface, shallow and deep solutions, using matched bandpass filtering. For each depth slice, derivatives such as vertical derivative, analytic signal, horizontal gradient magnitude and local wavenumber were calculated to characterize and map edges of geologic features (igneous bodies, faults etc.) and terranes. Results from remote sensing analyses indicated major NE-SW and ENE-WSW structural trends with minor NW-SE and WNW-ESE trend directions while a major ENE-WSW and a minor NNE-SSW structural trend were observed from both gravity and magnetic data. A zone showing centres of magmatic intrusions concentrated towards the Eastern part of the area trending in a major NE-SW direction was effectively delineated from magnetic data while the gravity data show similar NE-SW trend direction of high and low density structures which we interpreted as areas of antiform and synform respectively. Finite local wavenumber, tilt and the 'thickness corrected depth' (TCDepth) methods were used to estimate and map the depth to the basement and sedimentary thickness, and we found them to be at an average of 7 km deep and 6 km thick respectively. The crustal structure of the area mapped indicates thinning towards the southern part of the area where there is thick sediment cover and thickening towards the northern part where there is thin sediment cover. 3D gravity inversion was used to map the architecture and estimate the depth to Moho using the Parker-Oldenburg method while the Li and Oldenburg Method was used to map out 3D density structure of the area. The Moho interface was estimated to be at about a 23 km deep while the 3D density structure of the area shows a major high positive structural feature trending NE-SW at the centre of the area bounded in all sides by deep-seated fault systems. Our study has shown that the general tectonic trend directions of the basin structures, the restricted location of the intra-sedimentary intrusive/extrusive rocks as well as the 3D basin structures agree well with the NE-SW trend of the Chain and Charcot fracture zones in the Mid Atlantic Ocean, hence, showing the possibility of these deep-seated basement structures influencing the general structural architecture of the trough.

**Keywords:** Matched bandpass filtering, Magmatic intrusion, Directional filters, crustal structure, inversion

# Poster Abstracts

Characterisation of submarine mass wasting deposits using 3D seismic reflection data: West Iberia Margin, Spain.

Daniel O'Connor, Prof Tim Reston, Dr Carl Stevenson

University of Birmingham

Submarine mass wasting events transport large quantities of material which can damage seafloor infrastructure or form tsunamis that can endanger human life. 3D seismic reflection data from the West Iberia margin has been used to analyse the extent and internal architecture of two buried mass wasting deposits to examine how the internal structures relate to their emplacement. The Galicia Slump Complex is located on the eastern flank of a peridotite ridge in the Deep Galicia Basin and is comprised of a larger mass wasting deposit called the Southern Galicia Slump (SGS) and a smaller deposit called the Northern Galicia Slump (NGS). The SGS covers a surface area  $49.8\text{km}^2$  and has maximum volume of  $11.8\text{ km}^3$ , making it one of the largest mass wasting deposits identified in the Galicia region. The maximum thickness is 465m which suggests it has been considerably over thickened relative to its length and width. This size may also be an underestimation as the base of the smaller NGN has eroded into the top of the SGS. The NGN which is much smaller in volume ( $2.79\text{km}^3$ ) is also much thicker than other submarine mass wasting deposits of a similar size, reaching 212m at its thickest point. Internal folding and thrust faulting within the slump deposits has been identified in the seismic data and the over thickening relative to their length and width dimensions is attributed to shortening by these structural features during emplacement.

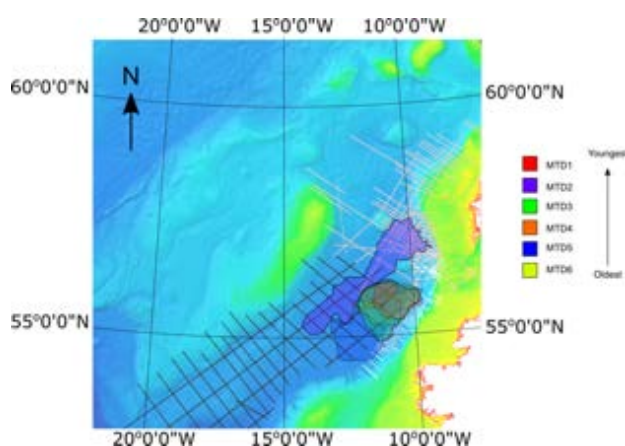
## **Seismic Analysis and Volumetric Estimations of Mass Transport Deposits in the Rockall Trough.**

***Roseanna Bentley, Murray Hoggett and Stephen Jones***  
***University of Birmingham***

Mass transport deposits (MTDs) are submarine landslides that move downslope, translating unconsolidated sediments along a basal shear surface. Deep water MTDs are observed from slope to basin-floor in submarine basins around the world and form a fundamental process in the evolution of the world's margins, accounting for up to 70% of the stratigraphy in some places.

The study encompasses the Rockall Trough, a NNE–SSW trending, elongate, 2–3 km-deep bathymetric depression situated on the continental shelf west of the UK and Ireland. Six MTDs have been identified for the first time using a large grid of public and proprietary 2D seismic data that spans the entire trough.

We recognise 2 overarching MTD systems. The first, consists of MTDs 1,3,4,5 and 6, which are debris flows and slumps starting from the low-slope and ceasing in the SE basin floor. The second system comprises MTD2 only, a slump deposit originating from the NE Rockall Trough; which may be part of the Peach Debrite Complex but is considerably larger than previously documented. The estimated ages of the 6 MTDs range from 160 ka–3 Ma. The largest deposit (MTD5) has an area and volume of 21,890 km<sup>2</sup> and 2,184 km<sup>3</sup> respectively, making it among the largest MTD so far reported. Kinematic indicators—geological structures that document the mode of movement at the time of deposition—were used to understand the rheology, type and movement direction of each MTD. We evaluate the mechanisms that triggered these landslides, including rapid sedimentation of the eastern margin of the Rockall Trough, the proximity to the Anton-Dohrn Lineament and glacial influences from the Mid-Pleistocene onwards.



*Bathymetric base-map showing the location and extent of the six MTDs documented by this study. Outline of Irish coastline (SE corner) conveys the location within the NE Atlantic. Coloured lines represent the different seismic surveys: black – Irish Petroleum Affairs Division, light pink – UK Oil and Gas Authority, white – proprietary data kindly provided by Spectrum.*

## **Porosity evolution in fault rocks at the brittle ductile transition.**

Francesca Prando <sup>1</sup>, Luca Menegon <sup>1,2</sup>, Katie Jones <sup>1</sup>, Florian Füsseis <sup>3</sup>, Mark Anderson <sup>1</sup>, Giuliano M. Laudone <sup>1</sup>.

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Pore fluid pressure plays an important role in the behaviour of faults at the brittle- ductile transition. Porosity is a key parameter controlling permeability and fluid infiltration, which in turn control rock strength and can determine switches from dominantly viscous to brittle fault slip behaviour. The nature and evolution of porosity of fault rocks is therefore important to understand their physical properties and rheology at the brittle ductile transition. In this study x-ray micro-computed tomography ( $\mu$ CT) and mercury intrusion porosimetry for multiscale quantification of the 3D pore space are combined with scanning electron microscopy analysis to examine microstructures related to the porosity evolution. Object of the study is a horizontal cored drill hole across a strike slip faults (fault BFZ045), collected at a depth of  $\sim 423$  m in the Onkalo nuclear waste repository, Olkiluoto, Finland. The fault develops within migmatitic- and granitic gneisses and contains a 0.5 m thick ductile, mylonitic precursor that formed under upper greenschist facies conditions. The brittle fault core of BFZ045 consists of a network of quartz and chlorite rich veins and cataclasites that occur both along the mylonitic foliation and discordant to it. However, brittle deformation of BFZ045 is entirely confined within the volume of the mylonitic precursor, with only minor cracks and chlorite veins occurring in the gneissic host rock at a distance  $< 20$  cm from the mylonitic shear zone boundary. The mylonitic shear zone and the brittle fault rocks have the same sinistral strike-slip kinematics. We analysed samples taken from the: (i) mylonite, (ii) chlorite rich cataclasite and (iii) chlorite and quartz veins.

We observed low porosity values ( $< 1\%$ ) characteristic of the granitic host rock, with minimal changes from the ductile precursor (0.10-0.14%) and the chlorite veins (0.06-0.20%).

Cataclastic samples have higher porosity, although still modest (up to 0.9%). Overall the pore throat size distribution obtained from mercury intrusion porosimetry ranges between 3 to 16  $\mu\text{m}$  in diameter. Maximum pore equivalent diameter observed are on the order of 40 to 500  $\mu\text{m}$ , due to the voxel resolution of 20  $\mu\text{m}$  used for  $\mu$ CT. In the  $\mu$ CT scans, different porosity type was identified as: (i) microcracks, (ii) isolated pores and (ii) clustered pores, mostly observed inside porphyroclasts in the mylonite. SEM images show that pores are present inside feldspar porphyroclasts and at quartz grain boundaries. Quartz in the mylonite and especially in the chlorite-quartz veins present pitted grain boundaries, and pore size on the order of  $\sim 10$   $\mu\text{m}$ , comparable with the mercury intrusion porosimetry results.

We observed a change in the distribution of porosity between the host rock intruded by chlorite veins, where porosity is controlled by feldspar and microcracks, and the ductile precursor, with a localization of porosity in the porphyroclast and at the quartz grain boundaries. Pitted grain boundaries of quartz appear to be the controlling porosity microstructure in the cataclasite and chlorite and quartz rich veins.

While mineral composition might affect the overall porosity estimate of the studied samples, we suggest that the observed changes may relate to dynamical cycle of fracturing and sealing mechanism.

## Microstructural evolution during solution precipitation creep

Amicia Lee<sup>1\*</sup>, Holger Stünitz<sup>12</sup>, Matheus Ariel Battisti<sup>3</sup>, Jiří Konopásek<sup>1</sup>

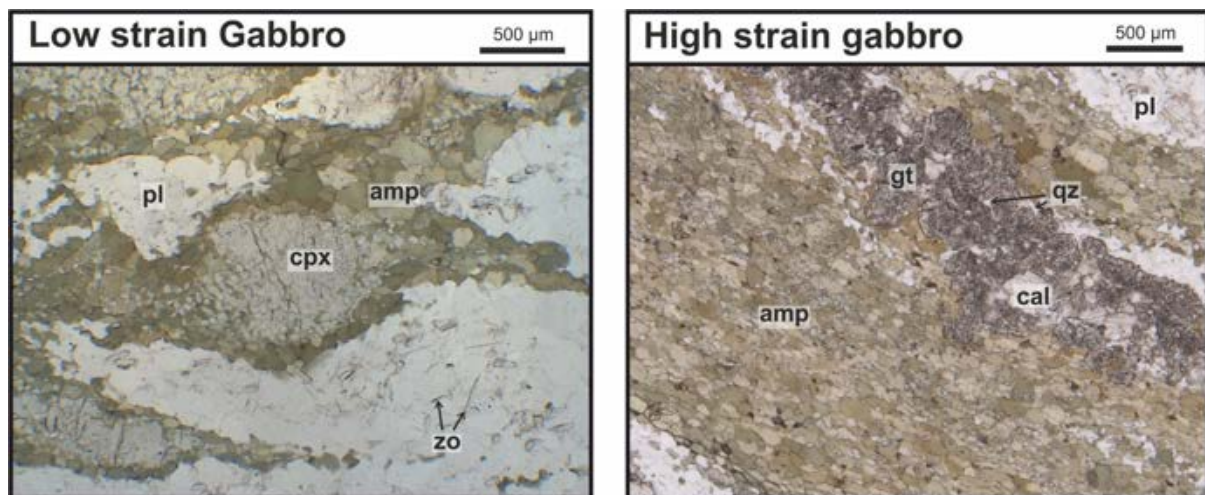
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Strain localisation and fabric development in the lower crust is controlled by the active deformation mechanisms. Understanding the driving forces of such deformation aids in quantifying the stresses and rates of the deformation processes. Here we show that diffusion creep plays a major role in deformation of gabbro lenses at upper amphibolite facies conditions. The Kågen gabbro intruded the Vaddas Nappe at 439 Ma at pressures of 7-9 kbar, temperatures of 650-900°C and depths of 26-34 km (Faber et al., 2019, Solid Earth). The margin of the Kågen gabbro on south Arnøya is made up of undeformed gabbro lenses with sheared margins wrapping around them. This contribution analyses and compares the microstructural fabric of the low strain gabbro and high strain margins. Microstructural and texture data indicate that preferential crystal growth of amphibole grains in the extension direction has produced the deformation microstructure and the CPO. The dominant deformation mechanism is inferred to be solution precipitation creep, where dissolution of the gabbro took place in reacting phases of pyroxene and plagioclase, and precipitation took place in the form of new minerals, amphibole, garnet and zoisite. Deformation and metamorphic reaction were both important transformation processes during diffusion creep deformation of the margins of the gabbro lenses. The weakening is directly connected to a transformation process that facilitates diffusion creep deformation of otherwise strong minerals (pyroxene, garnet, zoisite) at far lower stresses than dislocation creep.



# Investigating Wear Rate and Frictional Behaviour of Porous Geomaterials Using Sintered Glass Analogues

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Shearing in natural geological environments such as faulting, slope failures, landslides and glacial abrasion involve a variety of geomaterials. Despite experimental investigation by multiple studies, the varied and heterogeneous nature of geomaterials means that the individual controls of material properties (such as porosity) on friction and wear remains largely unconstrained. Porosity adds an inherent roughness through the interaction of pore margins and the slip surface acting to concentrate stress onto a smaller slip surface area, encouraging comminution. This comminuted gouge alters slip behaviour, reducing shear stress and potentially dissipating the heat generated by friction. In volcanic environments, this is further complicated by the presence of interstitial glass that affects the slip behaviour through its complex rheological response to rapid changes. Lavallée et al. (2015) showed that heating rate during frictional sliding influences the rheological response as glass reaches and exceeds the glass transition temperature ( $T_g$ ), which may cause catastrophic fragmentation in certain conditions.

We produced samples with varying porosities (~10%, 20% and 30%) by sintering soda-lime spheriglass beads for different timescales (after Wadsworth et al., 2016). These were tested at different slip rates ( $0.1 - 1.0 \text{ ms}^{-1}$ ) and low normal stresses ( $0.25 - 1.0 \text{ MPa}$ ) using a low to high velocity rotary shear apparatus to examine the mechanical behaviour and wear rate. Temperature change throughout the experiments was additionally monitored using a FLIR thermographic camera.

Friction coefficients were higher for samples with higher porosities, with 30% porosity samples following Byerlee's friction law, and the 20 and 10% porosity sample sets having progressively lower friction coefficients. At higher slip rates, all samples exhibit slip weakening behaviour, where friction coefficients drop by around 0.2-0.3 from  $0.3 \text{ ms}^{-1}$  to  $0.5 \text{ ms}^{-1}$ . This is either due to slip plane evolution or temperature activation. Only the 30% porosity samples showed visible comminution, with wear rates exceeding 0.72 mm per metre of slip at highest slip rate at normal stress. Denser samples exhibit much lower wear rates (values had to be corrected for thermal expansion which dominated the change to monitored sample pair length during slip). The magnitude of temperature change due to frictional heating scaled with increasing applied normal stress and imposed slip rate. Experiments with higher wear rates, which had the highest friction coefficients also resulted in lower temperatures due to heat dissipation.

Lavallée, Y., et al. 2015. PNAS, 112(30):9276.

Wadsworth, F.B., et al. 2016. Proc. Royal Soc. Lond A:472(2188).

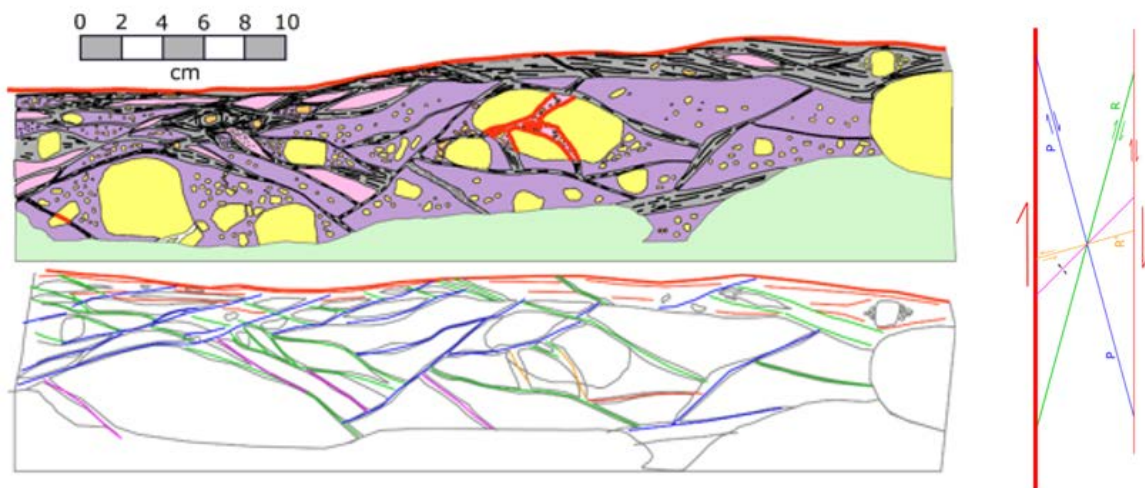
## ***Fault mapping of UK Carboniferous Coal Measures over four orders of magnitude: insights into fault-rock development.***

*Billy J. Andrews; Zoe K. Shipton; Richard Lord*

*Department of Civil and Environmental Engineering, University of Strathclyde.*

Faults may act as a conduit, baffle, or conduit to fluid flow and affect the strength of a rock mass with the behaviour of a given fault greatly affected by the internal structure of the fault zone, orientation of fault strands, and distribution of low-permeability fault rocks. Understand fault rock development and the internal structure of faults cutting coal-bearing sequences has several industrial implications including hydrocarbon extraction and the increasingly important field of low-enthalpy mine geothermal. Despite this interest, research is limited into how mechanical stratigraphy, the presence of a naturally fractured lithology (coal), and abundant sub-bed scale heterogeneities affects fault-rock development in these successions. To address this we investigate several fault zones through geological mapping at a number of scales (1:2,000, 1:100, 1:10, and 1:1) accompanied with detailed field observations. We present findings from two coastal field sites (Whitley Bay and Howick) in the Northumberland Basin, NE England, which display exceptional exposures of UK Carboniferous Coal Measures.

We find that FW fault-strands are more planar, both in map and section view, and often develop a laterally continuous zone of fault rock up to 30 cm thick (cataclasite, fault-breccia, and fault-gouge). This is followed by a zone immediately towards the HW where fault-core lenses and subsidiary faults dominate which typically have strikes of 15°, 30°, or 45° to that of the Primary Displacement Zone (PDZ). Across all scales of observation, the orientation of fault-rock and subsidiary strands fit a dextral Riedel shear geometry with the orientation controlled by the major feature for that scale (see figure). Minor fault strands develop discontinuous fault-rock including pods of matrix-supported fault breccia with calcite cement. This coupled with the distribution and orientation of veining and alteration, suggests abundant off-fault fluid flow through the HW damage zone. Aspect ratio of clasts and lenses increases towards the PDZ for clasts/lenses above 1 cm<sup>2</sup>; however, for clasts smaller than this grinding causes aspect ratio to decrease. Geometrical asperities are common, likely caused by the presence of abundant sub-bed scale heterogeneities (e.g. mud-draped ripples) which lead to the development of a heterogeneous stress field during faulting. T-shears and asperities within heterolithic units promote the formation of off-fault pods of fluid-assisted fault breccia within competent beds.



# **Fluid Flow in an Exhumed Geothermal System: Hydrothermal Vein Morphology and Composition within the Atacama Fault Zone, Chile**

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## **Abstract**

Geothermal reservoirs require high permeability to sustain fluid flow, which is often controlled by fracture networks. Mineral precipitation in veins within these fractures records interaction between fluids and deforming crust. Vein properties, such as mineralogical composition, chemistry, orientation, thickness and texture, are representative of vein formation processes. Understanding these processes in an exhumed geothermal system is fundamental to efficiently exploiting modern geothermal systems in similar tectonic settings. The ~NNW-SSE Bolfin Fault, in the Atacama Fault Zone, Chile, is one of several overstepping sinistral strike-slip faults that bound an extensional duplex, which is considered to be an analogue structural setting for a large proportion of geothermal systems. The Caleta Coloso Duplex comprises rotated blocks of granodiorite, bounded by transtensional NW-SE second order faults, overprinted by ~N-S and ~E-W third-order extensional faults. Structural transects and vein maps were made within the permeable damage zones of the faults, which are extremely well exposed due to the hyper-arid climate. Systematic samples were analysed petrographically and geochemically in order to constrain precipitation phases in different parts of the fault system. Three principal vein-forming events were observed to overprint, and occasionally exploit, earlier ductile deformations, forming an interconnected vein network: epidote-quartz, quartz, and calcite-palygorskite-salt. Epidote-quartz and quartz veins commonly show broadly coeval relationships and hydrothermal brecciation, defining a period of energetic and episodic fluid flow under similar conditions. Vein thickness generally correlates with fracture orientation, with flow apparently controlled by a few wide fractures that occasionally display evidence of crack-seal mechanisms. Early and late precipitation phases form in different parts of the fault damage zone, suggesting early phases have significantly reduced permeability and/or increased rock strength. Host rock alteration is most evident at a fault bend within the duplex, suggesting greater percolation of fluids in this structural configuration. Future work aims to further consider the microstructural textures of veins, as well as individual crystals, in order to quantify mineral precipitation rates and pressure/temperature conditions of precipitation.

## **Seismic analysis of the Galician Margin, West of Spain, using attribute maps of the S horizon to determine basin kinematics and serpentinization.**

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<sup>2</sup> School of Geography, Earth and Environmental Sciences, University of Birmingham, UK

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### **Abstract:**

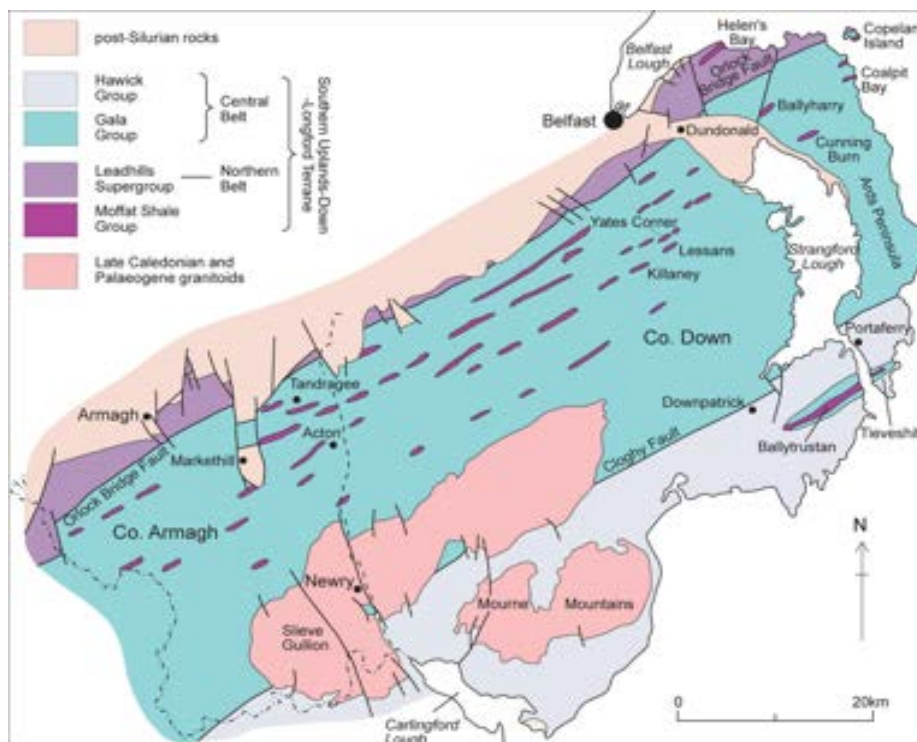
This project seeks to use the 2013 Galicia 3D seismic dataset to understand the kinematics of a hyperextended rift system. The rifting seen in the Galicia margin occurred during the Late Triassic to Aptian (Mid Cretaceous). The Galicia 3D volume permits us to observe the structures of the hyper-extended continental crust in unprecedented detail: normal faults are a prominent feature of the margin and root on the S horizon, which is a corrugated surface identified by a bright reflector and interpreted as a low angle detachment fault. A structural analysis of the fault network at the Galicia margin has also revealed that the faults were active down to an angle of 40°, surprisingly low for normal fault activity. We suppose that prolonged activity of the faults down to 40° was permitted by the presence of serpentine underneath the S, a weak rock formed by hydration of mantle peridotites. The main method of data analysis will be through the generation of attribute maps using Kingdom (2015) software. These attribute maps will be applied to the S surface and a combined fault and S horizon with the aim to: identify further kinematic markers at the surface of the S, zones of serpentinization underneath the S, help understand the link between serpentinization and faulting and determine the age of faulting. Studying the Galicia margin will allow us to better our understanding of the relationship between serpentinization and the creation of a weak decollement layer that subsequently underwent shearing during rifting extension.

## Mapping and Structural Geology of the Lower Palaeozoic Longford-Down extension of the Southern Upland terrain in Northern Ireland

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Geological Survey of Northern Ireland (GSNI), Belfast, BT4 3SB.

GSNI survey mapping of the Lower Palaeozoic, Longford-Down (Figure) extension of the Southern Uplands terrain is approaching completion. Fieldwork and in particular detailed surveys of 17 quarries across the region have yielded a wealth of structural data that reveal the presence of the following dominant fault sets: NNW-SSE to NW-SE dextral, NNE-SSW to NE-SW, N-S and W-E sinistral. Stereonet plotting and analysis of fault data show these fault sets to be relatively consistent across the terrain.



Relationships of faulting in the Lower Palaeozoic host rocks with Late Caledonian magmatism, are observed at igneous complex scale where two plutons of the Newry Igneous Complex have roughly rhombic shape, supporting the idea that space for their intrusion was created by sinistral transtensional shear on NNE-SSW and NE-SW structures.

In terms of fluid flow, NNW-SSE to NW-SE dextral faults are most likely to develop fault breccia and are most often associated with groundwater ingress. Whilst NNE-SSW to NE-SW sinistral faults are most often mineralised and host calcite-dolomite, baryte, pyrite and chalcopyrite. In the NE of the region at Whitespots-Connlig, vein hosted galena, associated with a NNE-SSW structure, was mined during the 19<sup>th</sup> century.

Most Palaeogene dykes in the region are hosted by NNW-SSE to NW-SE dextral faults, and it is not uncommon for the dykes to have one or both margins faulted indicating that the faults have moved post intrusion. Brecciation of the dyke also promotes their involvement in groundwater flow.

# **Challenges in the subsurface interpretation of a fold and thrust belt and how to get the best insights: an example from Eastern Carpathians Bend Zone, Romania**

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Key words: seismic interpretation, analogue modelling, salt tectonics, fieldwork, injectites

Fold and thrust belts are a notorious challenging environment when it comes to providing structural models for the subsurface, and the Eastern Carpathians Bend Zone is no exception. Hosting the largest onshore oil fields in Romania, this is a highly mature hydrocarbon area, with most of the fields producing since the late nineteenth century. Characterised by superimposed tectonic events, most notably the mid-Miocene compression (when most of the shortening occurred) the area is also well known for multiple detachment levels and salt tectonics. As a consequence the reservoirs, especially the Oligocene - lower Miocene (sub-salt), thought very prolific are structurally complex, heterogeneous and compartmentalised. It is a constant struggle for the geologist to create structural maps of these reservoirs due to complex deformation, inconsistent data and poor seismic resolution. Some of the most significant issues are related to scattering of dip data and the overall difficulties in correlating well logs. In some cases, even the logs of the side-track well do not correlate with the initial log.

Scaled analogue models coupled with seismic interpretation and the study of surface exposures has been carried out in order to get insights into these complex subsurface reservoirs. The analogue models and seismic interpretation provided key insights into the overall fold and thrust belt geometry and revealed the sub-salt as well as supra-salt structural style. The models are characterized by supra-salt detachment folds formed above sub-salt (Oligocene - lower Miocene) duplex structures and salt pillowing in the core of these anticlines. Low angle thrusts in the near vertical limbs of the detachment folds are observed in all experiments.

The detailed fieldwork revealed that first, at the outcrop scale significant folding occurs in the Oligocene-lower Miocene sequence. Upright, gently plunging folds as well as overturned and recumbent folds are possible. Fold limbs are occasionally cross-cut by forethrusts or backthrusts. Also, parasitic folds and fold-accommodation faults have been identified. Apart from this rather complex but typical tectonic structures, a network of sand intrusions is also present in the Oligocene - lower Miocene sequence. The dyke networks are intersecting the adjacent rocks at high angles and appear to follow fold-related fractures. Also, some preserved fluidized layers respond to fold tightening by thickness redistribution and intrusion. Injection is therefore considered to be syn-kinematic with the mid-Miocene tectonic stage when most of the shortening in the area occurred. Their presence can explain some of the reservoir heterogeneities and challenges in well correlation.

Experimental results show the overall fold-belt geometry position of the duplex structures and highlight the complex geometries that can be expected both sub- and supra-salt layers, while the surface exposures gave valuable insight into reservoir-scale structural style.

We suggest that integrating the subsurface data, analogue modelling and fieldwork provides key insights into regional to reservoir-scale possible structures, which can aid in both mapping and predicting the subsurface structures.

# Kinematic structures unravel distinct shear directions in highly-welded ignimbrites at topographic barriers

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Kinematic indicators observed in exhumed deep crustal shear zones commonly have undergone long-term high P/high T conditions and shear-stress. By contrast, structures, fabrics and kinematics in highly-welded ignimbrites result from short-term rapid shear-stress exerted by a searing-hot and fast flowing pyroclastic density current on aggrading pyroclastic material. During progressive aggradation, the searing-hot and ductile particles instantly fuse together and become sheared in non-coaxial strain to generate spectacular shear-structures. Subsequent cooling thus ‘freezes’ the shear sense indicators into the solid deposit, now being incapable of secondary remobilization. A fundamental aspect of unravelling volcanic successions worldwide is the precise determination of the current flow direction from its deposit providing key information on (1) its source location and (2) its interaction with topographic barriers and thus hazard potential.

We are using micro- to macroscopic fabrics and kinematic structures in highly-welded ignimbrites as such have the potential to precisely record critical information on the currents flow direction and interaction with local to regional palaeotopography. We show that elongation lineations and other distinct shear structures carefully respond to varying local topography. These can be used to differentiate and understand early formed, rapidly chilled structures in the basal vitrophyre that record the current transport direction from subsequently formed slower chilled structures higher in the deposit that record the gravity-driven slumping direction on varying palaeotopography. This is leading towards an enhanced understanding of ancient palaeotopographic settings and large-scale caldera collapse events.

## **Honeycomb structures revealed on 3D seismic data in the North Falkland Basin?**

### **Poster**

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The North Falkland Basin, a Mesozoic-aged sedimentary basin, located 40 km north of the Falkland Islands, is a rift system comprising a series of offset depocentres. The northern part of the basin has a half-graben geometry with the depocentre-controlling faults located on its eastern margin. The main depocentre, the Eastern Graben has a proven petroleum system hosting stratigraphic and combined structural-stratigraphic traps (Liz, Zebedee, Sea Lion, and Isobel/Isobel Deep discoveries). In the shallow section overlying both this significant sedimentary basin, there are a selection of unusual features observable on 3D seismic data.

The features were initially attributed as sub-seismic polygonal faulting, but after more detailed investigation they appear to be very similar to honeycomb structures observed in the Great South Basin of New Zealand. These structures are observed at time-depths of ~680 -760 ms twt (60-150 ms twt below seabed) and cover an area of 1,400 km<sup>2</sup>. They appear as densely packed oval to polygonal depressions. The depressions appear to be limited stratigraphically, and occur within two reflectors. The depressions are typically 450-650 m across and have time-depths of 20 ms.

Previous authors have attributed the formation of these types of structures to diagenetic processes. Immediately above the honeycomb structure, there is a series of pockmarks that may be related to gas or fluid expulsion from the honeycomb structures. The depths at which they are found and the evidence of fluid expulsion suggests this could be due to the opal-A/CT transition. This contribution will provide a detailed discussion of the morphology of these structures and their relationship to the overlying fluid expulsion structures, as well as suggesting possible mechanisms for their formation.

## **Inversion of normal faults during magma emplacement in the shallow crust, Exmouth Plateau, offshore NW Australia**

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The emplacement of igneous sills in the shallow subsurface can drive uplift of the overburden and the free surface. Supra-intrusion uplift results in the formation of so-called *forced folds*, the dimensions of which depend on the size of the underlying intrusion, its rate of emplacement, and the host-rock rheology. Studying the geometry and growth of forced folds can help develop our understanding of: (i) how intrusion-induced ground deformation is expressed in active and ancient magmatic settings; and, (ii) the formation of economically important hydrocarbon traps in magmatically influenced basins.

Sill emplacement commonly occurs in sedimentary basins that are undergoing, or have undergone, tectonic extension. A consequence is that, prior to intrusion, the subsurface is dissected by normal faults. Magma movement through sedimentary basins, and the host rock deformation this drives, are likely to interact with these pre-existing normal faults. Despite ongoing research into forced fold evolution, the interplay between intrusion-induced uplift and normal faults is poorly understood. Here, we use borehole-constrained 3D seismic reflection data from the Exmouth Plateau, offshore NW Australia to answer two questions. First, can intrusion-induced uplift drive inversion of a pre-existing normal fault? Second, if so, what effect will this inversion have on normal fault geometry and in particular, displacement-length relationships? Our data are ideal to answer these questions, given the structural relationships between normal faults, igneous sills, and forced folds are superbly imaged at a relatively high (decametre-scale) resolution. We investigated two structural scenarios. In the first, sills are located in the hanging wall of major normal faults and terminate against the fault plane, such that the supra-sill forced fold is contained entirely within the hanging wall. The position of this fold indicates that only the hanging wall was uplifted during magma-intrusion. 3D analysis of fault throws indicates that parts of the faults adjacent to the sills were inverted during sill emplacement. In each case, the magnitude of inversion is less than or equal to the thickness of the sill and the amplitude of the forced fold. In the second scenario, sills cross-cut normal faults, such that forced folds occur in both the footwall and hanging-wall. Here, structural analysis of fault-fold interactions indicate that fault inversion occurred during magma-intrusion. However, in contrast to the first scenario described above, here the magnitude of inversion is consistently less than both the thickness of the sill and the amplitude of the forced fold. In both scenarios, localised fault inversion leads to departures from classic throw-length relationships for isolated and linked normal faults.

These results demonstrate that where pre-existing faults are present, intrusion-induced surface uplift can trigger fault inversion. This study hence provides new insights into the interaction between brittle and ductile processes during the evolution of forced folds. An additional consequence of this structural inversion is the modification of fault displacement-length relationships that record earlier stages of basin evolution; this has implications for understanding fault kinematics in other magmatic rift systems.

# The Relationship Between Short-Term Active Tectonics and Long-Term Mountain Building

Jack McGrath, Dr. John Elliott, Prof. Sandra Piazzolo, Prof. Tim Wright, Dr. Ian Hamling

The Alpine fault is a major strike-slip fault located along the west coast of South Island, New Zealand, forming as a result of a continental transpression between the Pacific and Australian plates. Oblique plate motions relative to the Alpine Fault has resulted in the formation of the Southern Alps mountain range following 90km of shortening. The relatively high plate motions (~ 39 and 10 mm/yr fault parallel and perpendicular respectively) means that exhumed material is still representative of the mid-lower crustal conditions in which they were deformed. This project will aim to combine short-term geodetic measurements with analysis of long-term deformational processes to achieve an increasingly holistic understanding of mountain building across variable time-scales.

The launch of the Sentinel-1 satellite constellation has allowed a vast increase in the amount SAR data available to carry out InSAR studies across the globe. With a 12-day repeat time between acquisitions, InSAR allows geodetic measurements to be made at temporal and spatial resolutions orders of magnitude higher than possible than with GNSS techniques. However, the Southern Alps remain a challenging target for such studies, with the sharp relief, high erosion rates and extensive snow and glacier cover resulting in significant seasonal coherence variations. However, by using a combination of persistent scatter and small baseline techniques, it has been possible to produce velocity maps from the west to east coast of South Island. By combining data from ascending and descending tracks, fault parallel and vertical uplift rates will be able to be resolved. This will allow small-scale variations in ground motion to become apparent, in addition to the distribution of strain across this plate boundary.

The lithology along the Alpine Fault is represented by a fairly laterally continuous sequence of mylonites in the near-field, through proto-mylonites to a highly veined quartz-mica schists. Although the mylonitic sequence has been extensively studied, including with the Alpine Fault Drilling Project, less work has been carried out looking into the deformation processes occurring in the proto-mylonites and schists. As such, much of the strain accumulation in this area is ascribed to the mylonites. Our initial studies indicate, however, that there may be a not insignificant degree of strain accommodated by the proto-mylonites and schists, due to mass transfer following extensive dissolution precipitation throughout these units. Analysis of samples taken from the field will constraints to be placed on the effects of such more distributed deformation, as well as inform numerical models of the convergence to recreate uplift rates observed along the Alpine Fault.

## **Carbon ordering by aseismic deformation: implications for crustal weakening and thermobarometry**

*Lauren Kedar, Clare Bond, David Muirhead – University of Aberdeen.*

Understanding crustal weakening is a vital component of determining the dynamic evolution of the Earth's crust. This can happen by numerous mechanisms, of which strain-related ordering is one which is particularly applicable to crustal weakening in shear zones. Previous field-based studies have focussed on collecting data from fault planes, as these provide a convenient way of constraining the extent of deformation. Experimental studies have monitored the effects of strain-related ordering in organic carbon on both fault surfaces and more distributed shear zones. These studies confirmed the occurrence of strain-related ordering at seismic rates, particularly in the form of graphitisation of carbon. However, these experiments showed the effects of strain-related ordering at aseismic rates to be limited when distributed shear zones were considered, in part due to the geological timescales required to emulate true conditions. In this study, we use Raman spectroscopy peak intensity ratios to study the ordering of kerogen in a field example of a distributed aseismic shear zone, an environment in which strain-related carbon ordering has not previously been documented.

Raman spectroscopy is commonly used as a non-destructive method of analysing the nanostructure of organic carbon, and is presently being developed as a powerful geothermometer. The nanostructural analysis is based on the comparison of spectral peak intensities, where one peak represents graphitic carbon (G-peak) and the other represents disordered carbon (D-peak). The ratio between these two peaks gives the degree to which the carbon has progressed from its original kerogen-like structure towards that of graphite. This progression can be due to increasing temperature or increasing strain, and until now the two effects have been difficult to separate. In this study, we use Raman spectroscopy peak intensity ratios to show that strain-related carbon ordering occurs across a 170m wide, 1km long aseismic shear zone in an overturned fold limb. Additional sampling through the overlying sediment stack allows us to differentiate strain-related spectral signals from those associated with temperature/pressure increases during burial.

In order to quantify the relative strain between the fold limbs and hence constrain the distributed shear zone, a strain rank score was developed based on calcite twin type, grain alignment, grain elongation and solution seam density. In the overturned, highly-sheared limb, type III calcite twinning was almost ubiquitous, greater grain elongation/alignment was observed, and a higher solution seam density was measured than outside the sheared fold limb. This evidence of increased strain in calcite coincided with a decrease in Raman D/G intensity ratios derived from organic carbon. At the same time, there was no evidence of any one limb having more or less external heat supply. As a result, we can justifiably separate the temperature-related and strain-related signals in the Raman spectra.

We infer, from previous studies, that strain-related carbon ordering encourages further strain partitioning in carbonaceous material, and may enhance zones of weakness in the rock. This ordering in aseismic shear zones has so far been unreported in nature, and so our field-based results are significant in supporting previous experimental evidence for this phenomenon. Our results also have implications for understanding dynamic crustal evolution, and will play an important role in the development of Raman thermobarometry, especially since current methods do not distinguish between strain-related and temperature-related ordering.

# **The fragmented evolution of the late Carboniferous northern British Variscan foreland basin; insights from Canonbie Coalfield seismic data, southern Scotland**

Louis Howell, Bernard Besly, Surika Sooriyathasan, Stuart Egan, Graham Leslie

## **ABSTRACT**

The complex characteristics of the northern British part of the late Carboniferous Variscan foreland are considered based on basin-wide burial history analysis, and seismic and borehole-based mapping of the late Carboniferous succession that is locally preserved at the Canonbie Coalfield. We suggest that late Carboniferous basins of northern Britain formed part of a spatially and temporally fragmented foreland basin system from early Westphalian (Bashkirian) until Stephanian (Kasimovian) times. At Canonbie, this is represented by repeated episodes of positive inversion, syn-depositional folding and unconformities within the Pennine Coal Measures and Warwickshire Group successions, whereas on a regional scale, it is represented by widespread accelerated subsidence rates, even beyond the traditionally recognised foredeep depozone. An initial (early Westphalian) episode of dextral wrench faulting along NE-SW orientated lineaments is recognised based on onlapping seismic reflector geometries against NE-trending mild positive inversion structures and contemporaneous NNE-trending syn-depositional growth folding and ENE-trending normal faulting. Higher magnitude, late Westphalian-Stephanian N-S orientated shortening, is recognised based upon tightening of these inversion structures and further onlapping reflector geometries. The main controls on early Westphalian subsidence within the northern British Variscan foreland were dextral wrenching and the overfilled nature of the foreland. Local inversion structures dictated local late Westphalian-Stephanian depozones, at which point the basin may have resembled a spatially fragmented, 'broken' foreland system such as that of Patagonia, South America. Local variations in crustal rheology, inherited fault strengths and their variation over time, fault orientation with respect to the evolving dominant stress field and mid-crustal detachments are suggested to play important roles in determining strain localisation, and ultimately the nature of these depocentres, at Canonbie as well as within other broken foreland basin systems.

#### **4-dimensional evolution of fault zones**

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Fault zones contain cumulative fracture damage sourced from both long-term quasi-static damage from interseismic period, and co-seismic fracture damage during an earthquake. A fractured fault zone will, therefore, have a complicated overprinting or cyclic damage. This means that identifying damage from individual earthquakes can be difficult.

In this work we use optical image analysis and cosmogenic nuclide dating to understand short- and long-term evolution of the fault zones, and in particular, attempt to identify damage from individual earthquakes. This is done by exploring the effect of multiple earthquake cycles on the deformation distribution related to 1959 M<sub>w</sub> 7.5 Hebgen Lake. Optical image analysis techniques such as COSI-

Corr and the Ames Stereo Pipeline (ASP) allow us to quantify the fault movement and the extent of the off-fault deformation from the last event. On the other hand, results from <sup>36</sup>Cl cosmogenic nuclide dating provide long-term constraints of the slip history. As it was shown by previous studies, the fault scarps re-activated in the 1959 event have previously experienced at least six earthquake events. Therefore, this allows us to differentiate fracture damage related to the last earthquake from the overall damage within a fault zone. Hence, comparing deformation distribution from the last to all previous events will help us to understand development of the off-fault damage as well as its effect on the fault zone evolution and seismicity.

We are hoping that outcomes of this work will improve our ability to understand and reliably predict fracture patterns and aid to our capability of seismic hazard forecast and mitigation. Additionally, as a part of the future work, we plan to re-evaluate the <sup>36</sup>Cl results from previous studies in the Hebgen Lake area. We also aim to apply these methods to other events such as 1954 M<sub>w</sub> 7.3 Dixie Valley and 2010 M<sub>w</sub> 7.2 El Mayor-Cucapah.

# Imaging dyke swarms in 3D: the power of seismic reflection data

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## Abstract:

Swarms of dyke intrusions extending for 10's to 1000's of kilometres can rapidly transfer large volumes of magma through the crust on Earth and other planetary bodies. There are three principal geometries of dyke swarms: (i) parallel or linear dyke swarms, which have widths of up to 10's km and form orthogonal to a horizontal, far-field  $\sigma_3$ ; (ii) radiating dyke swarms, which develop when  $\sigma_3$  is circumferential to a central source, such as a magma reservoir or mantle plume, and have widths of up to several 100's km; and (iii) giant circumferential dyke swarms, which can be up to several 100's km wide and emanate from the lateral termination of a plume head. Within these dyke swarms, component intrusions may be up to 10–100's m thick and are primarily accommodated by crustal extension, which imposes a regular spacing on dyke distribution. Due to their geometry and large scale, dyke swarm emplacement can drive crustal extension, thereby influencing plate tectonic processes on Earth and shaping other planetary bodies. Their unique morphology and short-lived emplacement history also means dyke swarms provide a record of syn-emplacement stress conditions and represent key spatial and temporal markers for palaeogeographic reconstruction. Furthermore, dyke swarm emplacement can promote accumulation of critical material resources and, if they feed extensive fissure eruptions, may modify the climate. Understanding dyke swarm emplacement is therefore crucial to a wide range of Earth Science disciplines. Yet the 3D structure of dyke swarms remains poorly understood because the nature of planetary surfaces means we can only quantify dykes on a pseudo-2D plane, which is dependent on swarm orientation, post-emplacement tilting, and erosion level.

To advance our understanding of dyke swarm emplacement and to test the validity of their properties predicted by surface-based analyses or various modelling approaches, we require a geophysical technique that can image their 3D structure at a decametre scale or better. Reflection seismology has proved a powerful tool for imaging the detailed structure of magma plumbing systems in 3D, but vertical dykes are expressed in these as subtle discontinuities that are commonly overlooked. Whilst dykes and dyke swarms have thus been recognised in seismic reflection data, we are not aware of any concerted effort to quantify their 3D geometry across broad areas. Here we use an extensive suite of 2D and 3D seismic reflection data from the North Carnarvon Basin on the Gascoyne Margin, offshore NW Australia, to characterise the structure of a previously unidentified dyke swarm; we name this the Exmouth Dyke Swarm. We mapped 26, N-trending, up to 155 km long, regularly spaced dykes distributed across  $\sim 40,000$  km<sup>2</sup>. Seismic-stratigraphic correlations and borehole data indicate all dykes were emplaced within Triassic and older strata and have heights of  $>9$  km. Overlying many dykes along their length are normal fault-bound graben and locally developed sub-vertical pipes, which extend up to and deform the Base Cretaceous unconformity ( $\sim 148$  Ma); we interpret these features as dyke-induced normal faults and pit craters, which implies dyking occurred in the latest Jurassic. Based on the presence of similar, potentially dyke-related normal faults and pits observed elsewhere in the North Carnarvon Basin, we suggest the Exmouth Dyke Swarm is  $>500$  km long,  $\sim 200$ – $300$  km wide, and radially disposed along a  $39^\circ$  arc centred on the Cuvier Margin. The geometry, age, and geodynamic setting of the Exmouth Dyke Swarm suggests it formed in relation to mantle plume activity. Our work demonstrates seismic reflection data is a powerful tool for identifying dykes and dyke swarms in sedimentary basins and along continental margins. Such data therefore provide a unique opportunity to examine the 3D structure of natural dyke swarms, allowing us to test hypotheses concerning their emplacement, how dyking translates to surface deformation, and their influence on margin evolution.

## Comparing predicted and observed discrete fracture networks

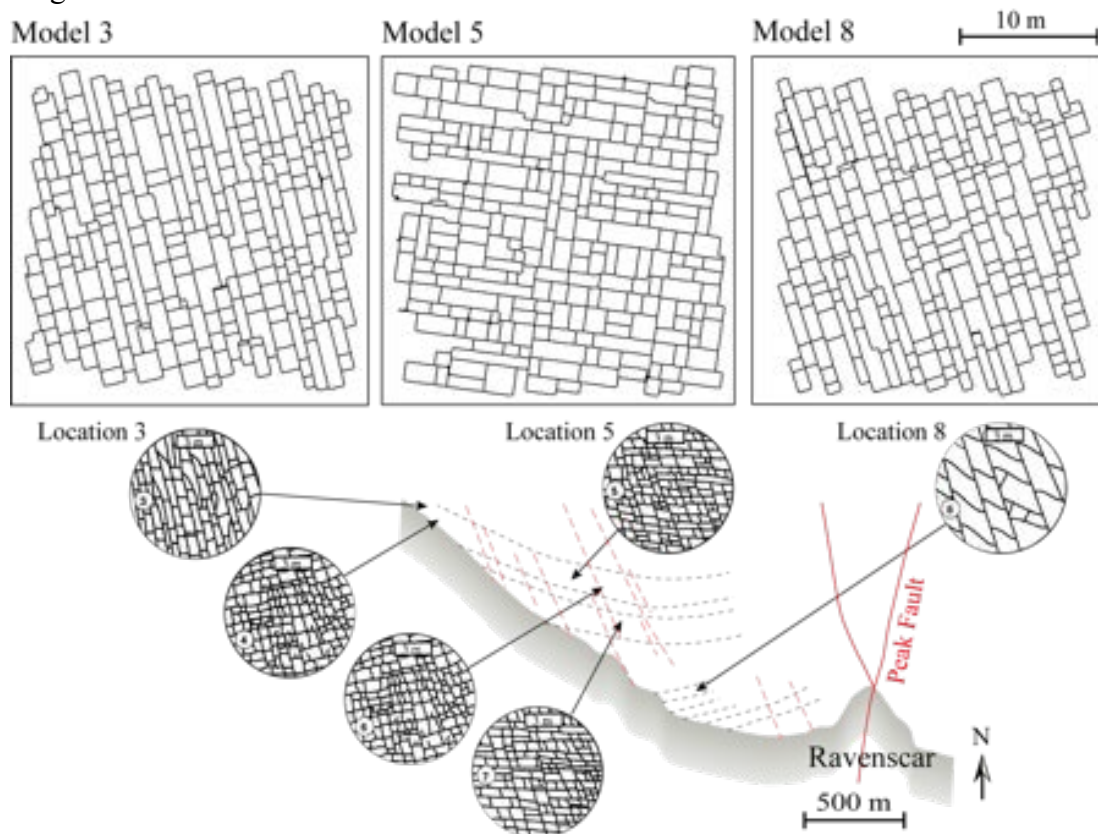
Oldfield, Simon J., Welch, Michael J. and L  thje, Mikael

Fracturing introduces heterogeneity and anisotropy to rock properties. Numerical simulation and mechanical experimentation has been used to explore these properties and their effect at all scales in both isolated individual fractures and connected fracture networks. However, consideration of connected fracture networks at kilometre scales in applied science and engineering are often limited by computational efficiency.

Using the method of Welch et al. (2019) we generate discrete fracture networks that feature fracture interaction and connection at the scale of hundreds of metres to several kilometres. Using geomechanical principles this approach aims to accurately represent a connected fracture network. Here, we refer to this as a connected Discrete Fracture Network (cDFN), emulating natural fracture size distributions and network anisotropy.

In this work we aim to compare the predicted and observed natural fracture networks. We have generated fracture predictions for field examples from the foreshores of Nash Point (Bristol Channel, UK) and Robin Hood's Bay (Yorkshire Coast, UK), previously mapped by Bourne & Willemse (2001) and Rawnsley et al. (1992), respectively.

Utilising published approaches in fracture topology (e.g. Sanderson & Nixon, 2015) and subsurface modelling (e.g. Thiele et al., 2016), we consider which metrics best suit comparison of predicted and observed fracture networks. Based on this work we consider future steps in validating the method.



Comparison of modelled fracture distributions and natural fractures observed by Rawnsley et al. (1992).

## **Outcrop characterization of fault damage zones: an example from the Araripe Basin, NE Brazil**

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### **Abstract**

Fault damage zones can strongly influence the subsurface fluid flow, including geothermal, groundwater, hydrocarbon migration and production, CO<sub>2</sub> storage and nuclear waste disposal. Fault zone architecture can be structurally complex and spatially variable with anastomosing shapes producing fault rocks that retard cross-fault flow or associated jointing and small-scale faulting, which may locally increase along-fault permeabilities. This work aimed to analyze the role of the brittle deformation of a segment of Patos Shear Zone, named as Triunfo Fault, located in the Northern border of the Araripe Basin, NE Brazil. We quantified the width of the Triunfo Fault damage zone in a well-exposed outcrop using the scanline technique, which provides an estimate of fracture density and frequency. Fractured rocks mainly compose the damage zone of Triunfo Fault: a) mylonitic orthogneiss (footwall) and b) sandstone and carbonate rocks (hanging wall). The fault core is composed of fault breccia and cataclasites that occur cemented by calcite. Due to the fault sinuosity and rheology heterogeneities, the width of the damage zone ranges from 240 to 290 m in the footwall, and 372 to 610m in the hanging wall. Our results indicate the following deformational phases: a) D<sub>n</sub>, Brasiliano Orogeny, transcurrent dextral shear zone represented by mylonitic foliation and folds in the host rocks; b) D<sub>n</sub> + 1, brittle-ductile deformation in the Paleozoic represented by a conjugate pair of strike-slip faults, tension gashes superimposed on mylonitic fabrics; and c) D<sub>n</sub> + 2, opening the South Atlantic Ocean (Lower Cretaceous) under a strike-slip brittle deformation represented by faults, shear fractures, deformation bands, veins, and joints. The main tectonic phase is represented by the brittle reactivation (D<sub>n</sub> + 2) of shear zones as normal faults (e.g. Triunfo Fault). We propose a tectonic evolution model for Araripe Basin under a predominantly strike-slip regime.

## **Structural controls on intraplate volcanism – The remarkably long-lived Tuatara Volcanic Field, New Zealand**

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Intraplate igneous activity is typically characterised by long geological records of volcanism spread over wide areas. Yet within such intraplate settings, individual volcanic systems are commonly spatially restricted and only active for relatively short (1-10 Myr) timescales. Understanding the hazards associated with intraplate volcanic systems active at the present day, as well as potential economic resources associated with these systems, thus relies on deciphering what controls their spatial distribution and temporal evolution. Whilst numerous studies allude to the role of pre-existing structures in directing magma pathways at shallow crustal depths, the full impact of structural inheritance on entire volcanic fields remains poorly constrained. Zealandia provides an excellent natural laboratory to investigate how crustal structure influences intraplate volcanism due to its: (i) protracted and relatively continuous record of diffuse intraplate volcanism across the continent over the past 85 Myr in response to localised lithospheric delamination; and (ii) its well-constrained basement geology onshore that can be extrapolated with confidence to offshore areas imaged in 3D in seismic reflection data.

We use borehole-constrained seismic reflection data to study a newly-discovered intraplate volcanic system, which we name the Tuatara Volcanic Field, buried offshore of the east coast of New Zealand's South Island. This 250 km<sup>2</sup> volcanic field is characterised by a large central dome, comprising stacked lava and hyaloclastite sequences, and over 69 volcanic cones. Seismic reflection data reveal the volcanic field is associated with >79 interconnected sills that, along with some isolated dykes, represent the volcano plumbing system. By determining the initial emplacement age of the sills and volcanoes, we show that volcanic activity occurred, likely incrementally, over a ~40 Myr period from the Late Cretaceous to Early Eocene, representing an unusually long-lived system. During this time, igneous activity migrated north-westwards across the volcanic field.

The location and migration of activity of the Tuatara Volcanic Field appears to have been controlled by the crustal-to-lithospheric scale Livingstone Fault, separating the NW-trending Caples and Dun Mountain ophiolite basement terranes. We suggest that the unusually long lifespan of this volcanic system may be driven by this lithosphere-scale structure acting as a focal point for detaching lithospheric material, inhibiting the annealing process and prolonging activity. The Tuatara Volcanic Field shares the same structural setting as the active Auckland Volcanic Field (0.14 Myr – present day) on the North Island, and may represent an ancient analogue superbly imaged in seismic reflection data. We show how crustal structure likely controlled the geometry, location and distribution of activity within the Tuatara Volcanic Field. Insights into the localisation and longevity of activity in this setting may also be applicable to understanding hazards associated with the Auckland Volcanic Field, its internal structure and future geological evolution.

# **The fault network along the western margin of the Falkland Plateau Basin**

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The reconstruction of the Falkland Islands microplate in a Gondwana pre-break-up configuration has been the subject of debate for decades. Previous reconstruction models position the islands off the south-east coast of South Africa, as part of a rigid Falkland Plateau fixed to the South American plate or undergoing a clockwise rotation of up to 180° during break-up. Our previous work, however, argues for less rotation of the islands needed during the opening of the South Atlantic. A drawback of the rotational model consists of a lack of documented evidence of this rotation in the sedimentary basins around the Falkland Islands.

This study addresses this issue by integrating 2D and 3D seismic reflection data and open-source gravity data in order to provide a new map of the structural framework of the two sub-basins east of the Falkland Islands, the Volunteer and Fitzroy sub-basins. This allowed us to constrain the Mesozoic evolution of the Falkland Islands microplate by interpreting the stress field variation around the islands in the context of Gondwana fragmentation.

Three main structural trends were identified along the western Falkland Plateau Basin. WNW-ESE trending half-grabens were mapped north-west of the Volunteer Basin. We correlate these with the linear gravity anomalies following the same trend in the Southern North Falkland Basin, north of the Falkland Islands. NNE-SSW normal faults swinging through N-S southwards are predominant west of the Volunteer Basin and are inferred to be controlling the entire western margin of the Falkland Plateau Basin. Locally, the NNE-SSW trend is subdued by NNW-SSE striking faults suggestive of left-lateral movement along a NNE-SSW direction. In the southern part of the Fitzroy Basin smaller scale faults are distributed in a Riedel shear geometry representing tensional T fractures and R, R' and P' shears supporting sinistral wrenching along the western margin of the Falkland Plateau Basin.

We consider these results to suggest intra-plate deformation that is consistent with a clockwise rotation of the Falkland Islands microplate. The correlation with the regional stress field supports the rotation estimated in our previous work and relates the basin formation along the Falkland Plateau with key events in the fragmentation of south-western Gondwana.

# Linking the activation of ancient structures and volcanism during rifting of the Red Sea, western-central part of Saudi Arabia

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Reactivation of continental basement structures during rifting can control rift fault patterns and basin architecture. Recent studies have shown that the obliquity of pre-existing anisotropies is critical to the style of overprinting. The western margin of Saudi Arabia offers an exceptional field site to understand the nature of interactions between ancient structure and rift-related volcanism and tectonics. The margin exposes a major Neoproterozoic terrane boundary – the Ad Damm shear zone (ADSZ) – which is oriented obliquely to the Cenozoic-age Red Sea rift axis. The ADSZ has recorded recent seismic activity, indicating the potential for such highly-oblique structures to have been reactivated during Red Sea rift evolution. The ADSZ is a NE-striking shear zone, which separates the lowlands of the Jeddah terrane in the NW, from the highlands of the Asir terrane in the SE. In detail, field mapping coupled with lineament extraction and fault-kinematic-data analyses reveal three main structural trends of Cenozoic-age faults and dykes: (i) Red Sea-oblique (N-S  $\pm 10^\circ$ ), (ii) Red Sea-normal (NE-SW), (iii) Red Sea-parallel (NW-SE). These sets record, respectively, maximum horizontal extension axes that are (i) E-W (ii) NW-SE, (ii), and (iii) NE-SW. Whole-rock geochemistry of Cenozoic dykes shows a wide range of chemical composition. However, current results indicate an orientation-controlled evolution in magma chemistry: (i) basaltic/rhyolite Red Sea-oblique dykes, (ii) basaltic andesite/trachyandite Red Sea-normal dykes, and (iii) tholeiitic basalt Red Sea-parallel dykes. Within the Ad Damm shear zone and Asir terrane, our data support non-coaxial strain involving Red Sea-oblique and Red Sea-normal faults that accommodate a combined ENE-WSW sinistral transtension tectonic regime, followed by Red Sea-parallel faults and dyke intrusion associated with regional Red Sea rift extension (i.e. NE-SW extension). A two-stage extension-reorientation is supported further by dyke geochemistry, as trace elements of the Red Sea-oblique and Red Sea-normal show relatively higher ratio in LILE/HFSE (e.g. Ba/Nb= 10-31) and LREE/HREE (e.g. La/Y= 0.3-1.32) from the Red Sea-parallel (e.g. LILE/HFSE (Ba/Nb= 7-10) and LREE/HREE (0.5-0.62)). The observed oblique ENE-WSW extension to the main Red Sea rift axis in the ADSZ and Asir terrane suggests the rift evolution was primarily controlled by ancient structures. This study, coupled with recent seismic activity along and adjacent to the ADSZ, has important implications for the reactivation potential of the ADSZ, and therefore seismic hazard within the area.

## **Structural Controls on Orogenic Gold in Northern Ireland: Insights from the Curraghinalt Gold Deposit**

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The Curraghinalt gold deposit (> 6 Moz) is located in the Sperrin Mountains of Northern Ireland and is one of the largest undeveloped gold mines in the world by grade. The high-grade mineralisation (15.02 g/t Au) is structurally hosted by 21 quartz-carbonate-sulfide veins that strike WNW-ESE and dip moderately to steeply NNE. The vein system connects two en-echelon brittle-ductile shear zones that strike E-W and dip steeply N. The deposit is hosted by Neoproterozoic metasediments (Dalradian Supergroup) which were thrust SE over an island arc – ophiolite complex (Tyrone Igneous Complex) in the early to mid-Ordovician during the final stages of the Grampian Orogeny. Despite the Curraghinalt vein system being located in a well characterised geological setting, previous studies have failed to agree on the controls and timings of the gold-bearing mineralisation.

Here, we present the results from detailed underground mapping to propose a new structural model for the Curraghinalt gold deposit. We reveal that the vein system comprises of right-stepping, moderately NNE-dipping sheared-laminated veins that are connected by steeply to subvertically NE-dipping dilational jogs and horsetail branches. These comprise of veins with a 'pegmatitic'-cockscorn-massive sulfide infilled texture that is relatively higher in grade than the sheared-laminated veins. We ultimately infer that the vein system propagated in response to normal-dextral kinematic movement (oblique-slip, N-side down) on the high-order en-echelon shear zones. From this, we hypothesise that the localised transtensional deformation corresponds to when the Dalradian metasediments were being thrust SE over a basement high. We also show results from the Cavanacaw gold deposit (20 km to the SE) to suggest that this model also accounts for the vein systems N-S orientation and sinistral kinematics.

## **The North Scotia Ridge and the South Falkland Basin Fold and Thrust Belt.**

### **Poster**

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Subduction beneath the South American plate along the Magallanes–Fagnano Fault becomes transpressional along the North Scotia Ridge, whereby the Burdwood Bank, has been accreted on to the southern margin of the Falkland Plateau. This activity formed the North Scotia Ridge (NSR), a seismically active, submerged, oblique-compressional plate boundary between the Falklands Plateau to the north and the Scotia Plate to the south. The nature of this plate boundary is still unclear, with both oblique convergence along a continuous fault or partitioned strain with parallel compressional and strike-slip segments being proposed.

Since the Eocene, the North Scotia Ridge has been the focus of compression and left-lateral strike-slip deformation. This deformation resulted in the downwarping of the underlying Mesozoic shelf, with reactivation and development of normal faults that displace both the basement and Cenozoic sediments, but also the development of an overriding northward verging fold and thrust belt.

This contribution provides a detailed description of the fault architecture of the area using a 2D and 3D seismic dataset, and highlights previously unrecognised NNE-SSW strike-slip faults that cross-cut the youngest thrust sheets. These structures are consistent with a prolonged history of partitioned sinistral deformation.

# The role of foliation and direction-dependent elastic moduli in fracture propagation; application to sill geometry

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Magmatic sheet intrusions – sills and dykes – are thought to propagate as hydrofractures, parallel to the  $\sigma_1$ - $\sigma_2$  plane. They are typically modelled as Mode I cracks in layered elastic media, where individual units are elastically isotropic and subject to a low deviatoric stress state (i.e. where principal stresses  $\sigma_1 \approx \sigma_2 \approx \sigma_3$ ). Many volcanic settings, however, are subject to deviatoric loading (i.e. where  $\sigma_1 \neq \sigma_3$ ), and the rock mass may have direction-dependent elastic moduli (e.g. Young's modulus,  $E$ ; and Poisson's ratio,  $\nu$ ) imposed by transverse isotropy e.g., bedding, foliations, and/or a pervasive fracture set. In such cases the relative orientations of the loading direction and the fabric can control overall intrusion geometry. To investigate the influence of loading direction on intrusion geometry in elastically anisotropic strata, we present the results of uniaxial compressive strength (UCS) tests, and non-destructive ultrasonic pulse transmission (UPT) tests on cylindrical core plugs of bedded and foliated metasedimentary Moine basement, cored parallel and perpendicular to foliation. The results are combined with X-ray micro-CT imaging of the fractured core plugs, and finite element (FE) simulations of sill propagation through horizontally or vertically layered media subject to an applied horizontal compression. Our experimental results are compared with the Loch Scridain Sill Complex (LSSC), Isle of Mull, Scotland: a suite of sub-horizontal sills that transgress at low angles through the sampled sub-vertically bedded and foliated metasedimentary Moine basement, and the horizontally bedded cover.

Anisotropy ratios  $A$ , (where  $A$  = perpendicular/parallel) determined from UCS and UPT tests show that the foliated samples display direction-dependency in: strength ( $A_{UCS} = 0.96$  to  $1.24$ ); static elastic moduli ( $A_{Es} = 0.77$  to  $0.92$ , and  $A_{vs} = 0.12$  to  $0.67$ ); and dynamic elastic moduli ( $A_{Ed} = 0.20$  to  $0.79$ , and  $A_{vd} = 0.22$  to  $0.60$ ). Samples loaded parallel to foliation are weaker (lower UCS), stiffer (higher  $E$ ), and less compressible (higher  $\nu$ ) than those loaded perpendicular to foliation. UPT tests conducted on critically stressed (taken to  $\sim 80\%$  UCS) and failed samples demonstrate that increasing damage causes  $\nu_d$  to increase (up to  $262\%$ ) and  $E_d$  to decrease (to  $27\%$  of initial  $E_d$ ). The UCS tests and FE simulations produced comparable geometries to those observed in the LSSC: foliation-parallel loading produced extension to extensional-shear fractures oriented parallel and sub-parallel to foliation, similar to the LSSC sills in the horizontal cover. Foliation-perpendicular loading produced fractures that are locally stepped against subvertical discontinuities, similar to observed steps in the LSSC geometry.

We find similar geometries between natural sills and experimentally-produced fractures hosted in elastically anisotropic strata across six orders of magnitude (mm – km). Our results indicate that the magnitude of deviatoric stress has a primary control on sill geometry, whereas layering orientation and elastic anisotropy control the size of steps in the overall fracture plane. Furthermore, initially direction-dependent dynamic elastic moduli may homogenise during progressive loading: this has particular importance to monitoring magma migration and volcanic edifices where cyclic loading (e.g. due to inflation-deflation cycles) may weaken the rock mass (reduce  $E_d$  and increase  $\nu_d$ ), which may act to promote or inhibit future eruptions.

## **The occurrence of deformation bands in a fold-and-thrust belt – an example from the Silesian Nappe, Outer Carpathians, Poland**

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Deformation bands are small scale tectonic features. Their kinematics and microstructural properties can reveal regional scale deformation mechanisms as well as burial conditions. Therefore, they are a useful tool for structural history reconstructions. Deformation bands have been reported from the Silesian Nappe, which is a major tectonic unit within the Polish segment of the Outer Carpathians. The Outer Carpathians are an example of an alpine fold-and-thrust belt formed as a result of the progressive shortening resulting from the southward subduction of the European Platform below the Alcapa and Tisza-Dacia microplates and the subsequent collision. The resulting fold-and-thrust belt is a stack of north-verging nappes. The studied part of the Silesian Nappe is composed of large-scale, generally NW-SE trending folds and cut by fore-thrust and several back-thrusts. The outcropping strata (Oligocene) comprise intercalated shales and sandstones.

In the studied region, deformation bands are the earliest tectonic features and their origin predates folding. They typically cluster within thick-bedded sandstones. The microstructure of the deformation bands is diversified within increasing depth, showing granular flow, cataclasis and pressure solution features. We recognised two types of deformation bands: shear and compaction bands. Deformation bands were found under three (1-3) geological settings while a conjugate set of extensional shear bands was observed close to hinge of synclines (1), whereas conjugate set of contractional shear bands was encountered in the frontal part of the fore-thrust within its hangingwall (2). However, compaction bands are the most abundant deformation bands within the studied region. They are oriented perpendicular to bedding planes as a result of layer parallel shortening. They were found within the hangingwall of back-thrusts (3). Moreover, they were observed only within the uppermost part of a lithostratigraphic unit. In our interpretation, these compaction bands were formed during the nucleation of detachment horizons which could have preceded the development of the back-thrusts. Our results show that understanding the origin of deformation bands within fold-and thrust belts can improve regional tectonic interpretations.

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# Exploring Sill Emplacement and Morphologies within the Porcupine Basin

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**Abstract:** The Porcupine Basin is located to the Southwest of Ireland and is a prime example of a failed rift basin. The Basin is divided into two distinct areas based on multiple physical disparities resulting from asymmetrical rifting within a simple shear regime. A clear structure in the porcupine basin is the Median Rift; there is much debate over the structure's true nature/origin. The main arguments for its origin are that it derived from: a tilted continental block, serpentinised mud flat and extinct volcanic structures. For the purpose of this study, the latter shall be assumed to be true to support the understanding of relationships constraining sill morphology and emplacement behaviours within such a system. The data being analysed are wide-angle seismic sections from the southern basin. From identifying boundaries and relationships regarding pre, syn and post-rift sequences, high reflection structures, identified as sills, are fairly continuous and extensive in depth. Given the extensive rift faulting and later reactivation of faults, multiple faults of various types and scales can be identified. However, larger more dominant structures are more commonly aligned with those associated to rifted margins, i.e. horst, grabens, fault blocks. The pre-existing structures of weakness will affect the emplacement of sills and their extent through the country rock. The subsequent morphology adopted will be examined and compared. The understanding of the sills acting as a welding structure to potentially strengthen exploited faults may act as a preventative feature that limits the extent of future brittle deformation.

# Extensional structures in the crest of a basin-inversion anticline – insights from 3D seismic data, Danish Central Graben

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Post-extensional inversion of sedimentary basins is a widespread and well-known phenomenon, and a significant number of hydrocarbon reservoirs are found in structures generated by basin-inversion tectonics. Examples of inverted basins in the North-Sea area include the Sole Pit Basin (UK), Broad Fourteens Basin (NL) and the Central Graben (DK). As documented in the 1980s from 2D reflection-seismic data, gentle basin inversion took place in the Danish Central Graben especially during the Late Cretaceous- early Paleogene.

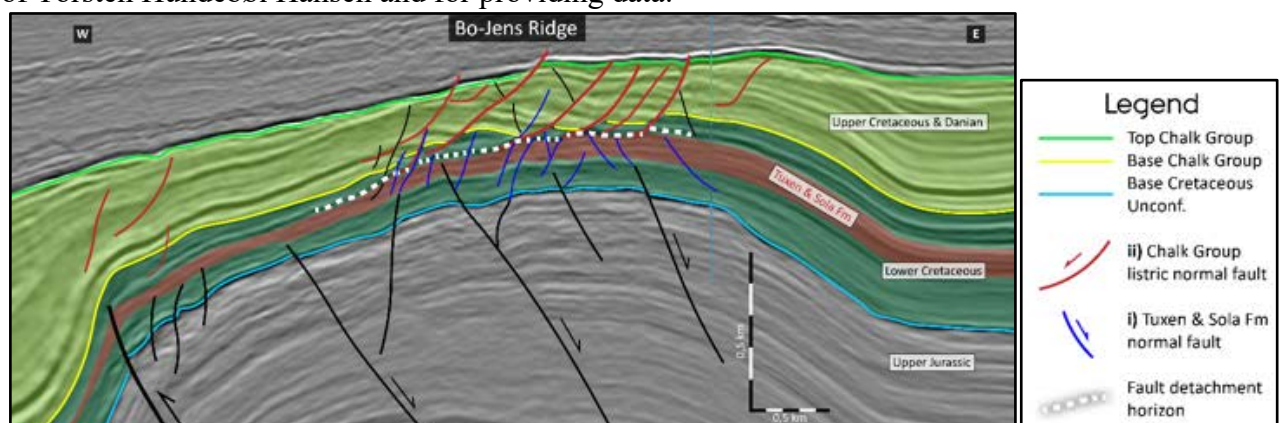
We have mapped faults, horizons, and seismic attributes from a depth-converted 3D seismic data set from the Danish Central Graben using state-of-the-art interpretation software. This means we are now able to look in closer detail at the inversion structures of the area and their internal deformation, and to provide a needed update to kinematic models for basin inversion.

One of the studied structures, Bo-Jens Ridge, is a large asymmetrical anticline. Although inversion is gentle on the basin scale, Bo-Jens Ridge reveals more intense deformation at the western edge of the uplifted area. Here it likely formed due to buttressing of the hanging wall associated with a Late Jurassic rift fault during shortening. Lower Cretaceous strata were rotated to near vertical angles in the western flank, and a variety of normal faults formed in the anticline crest.

Generally, we observe two types of crestal faults here: **i)** faults found in the pre-inversion strata, which are more abundant, closely spaced and show smaller throws relative to **ii)** syn-inversion growth faults located in the Late Cretaceous Chalk Group. The latter show significantly greater displacement and many detach in horizons just above the lower faults. Along most of the anticline crest, both fault types strike obliquely to its axis; we suggest a strike-slip component during inversion is responsible.

We identify no signs of compression in the crest of Bo-Jens Ridge, although the structure as a whole is clearly the result of lateral shortening during basin inversion. This, along with the local and stratigraphically partitioned extensional deformation, points toward a passive uplifting and forced folding (bending) of the shallow sedimentary strata during inversion. This could have had implications for the tight Lower Cretaceous reservoir in the anticline crest, the compartmentalization of which is poorly understood. This study has the potential to increase our understanding of deformation within basin inversion structures, including at sub-seismic scales.

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## The structure, kinematics and age of the Grampian Shear Zone

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The Grampian Shear Zone, is a boundary slide that separates the Badenoch group from the Grampian and Appin groups. The Lithologies within and below the Grampian shear zone show evidence for Knoydartian deformation while the Dalradian group lithologies structurally above the shear zone show only Caledonian deformation (Leslie et al 2013). Geochemical analysis of deformed pegmatites within the shear zone suggest that they are syn-shear pegmatic bodies, these pegmatites give a range of dates from 808Ma to 440Ma (Noble et al., 1996., Hyslop and Piasecki, 1999., Leslie et al, 2013). Two large pegmatites within the shear zone yielded U-Pb monazite and zircon ages of 840 - 806 Ma clearly showing that the shear zone was active during the Knoydartian (Hyton et al, 1999. Leslie et al, 2013). The relationship between the GSZ and the Grampian Group remains to be clarified and requires further data gathering and analysis (Leslie et al., 2013). There is unpublished BGS data that shows monazites within the Badenoch Group show complex histories with 1200Ma to 450 Ma Caledonian reworking ages (Leslie et al., 2013). The suggested basement cover relationship between the poly orogenic Badenoch Group and GSZ with the supposed cover sequence, the Grampian Group is unclear. Here we present our current research on the nature of this contact.

## **MICROSCALE CHARACTERISATION OF DAMAGE EVOLUTION IN CURLING STONES USED IN INTERNATIONAL COMPETITION**

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The rocks used to produce curling stones for international competition are only sourced from two localities in the world: Ailsa Craig, Scotland and Trefor, Wales. Curling stones consist of two components: (1) the running band (the ring-shaped bottom surface of the stone which rests on the ice) and (2) the striking band (the convex band on the profile of stones which collides with those of other stones). With a focus on the striking bands, we aim to document the damage evolution of curling stones using synchrotron microtomography (3D characterisation of pristine samples and 4D damage evolution), optical and scanning electron microscopy (quantitative characterisation of pristine samples and microfracture characterisation of damaged striking bands), and petrophysical testing (fracture characteristics and comparative data). These data will be complemented by an on-ice experiment that will determine the mechanics (*e.g.*, force, stress, velocity) of curling stone impacts. Out of four curling stone varieties (from Ailsa Craig and Trefor), we observe the striking bands of three varieties to show macroscopic, incipient to mature, curvilinear fractures. The curvature of these fractures is consistent and does not vary significantly between individual stones and between curling stone varieties. However, the degree of macroscopic fracture development differs between aged striking bands of curling stone types: Blue Trefor (macroscopic fractures not observed), Red Trefor (weakly incipient), Ailsa Craig Common Green (incipient to juvenile), and Ailsa Craig Blue Hone (juvenile to mature). Unfortunately, it is not possible to determine the degree of usage (age) of the selected samples and thus it is not possible to normalize these apparent differences in damage. Given that the striking band limits the lifetime of curling stones, understanding the damage evolution of curling stones can contribute valuable information to the maintenance of curling stones. The rock physics of curling stone impacts is linked to dynamic spalling and more broadly to rock failure, as these processes are ultimately related to the initiation and propagation of fractures.

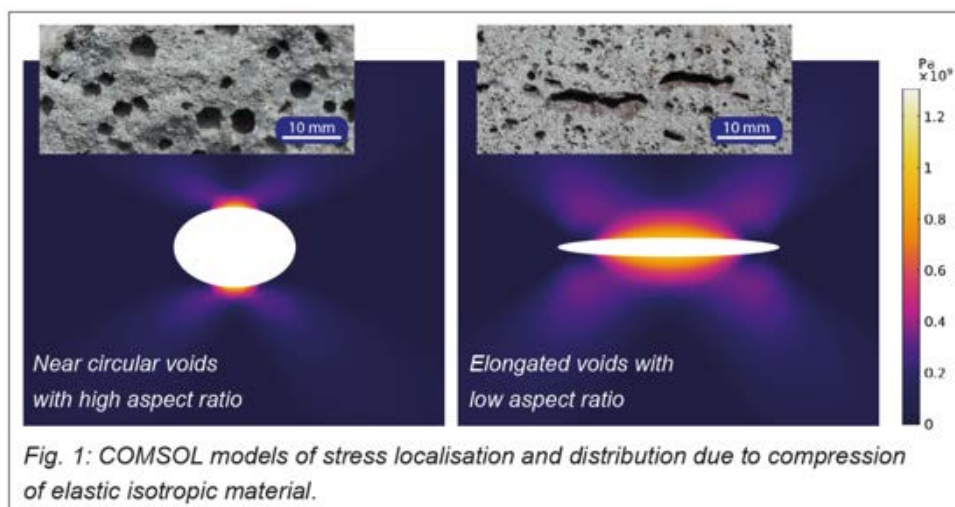
## Finite element models for a pore geometry control on fracture distribution and growth

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Accurate geohazard and geotechnical engineering characterisation are critically dependent on the determination of bulk rock strength. Rock strength has an inversely proportional relationship to porosity, with an increase in porosity resulting in a non-linear decrease in strength. This relationship is recognised for a number of natural and manufactured materials, but historically has been considered only in terms of the scalar quantity of porosity; the ratio of the pore volume to the total rock volume. However, Bubeck et al. (2017) showed that the relationship between porosity and the rock strength and stiffness are also dependent on the shape, aspect ratio and orientation of the pores with respect to the direction of the applied load. Here we build upon their characterisation of natural pore-geometry effects in basalts, using numerical simulation of crack growth in rocks hosting variably oriented and shaped voids. We consider that our simulations are applicable to any crystalline rock, in which the pore space is best approximated by isolated ellipsoids, e.g., vesicular volcanic rocks. We use the finite element modelling software COMSOL to simulate elastic deformation during the compression of basalt, to induce crack nucleation. Our initial models are conducted in a 2-dimensional rectangular model space, with embedded voids ranging in aspect ratio minor:major axes  $\frac{c}{a} = 1$  to 0.001. Simulations involve the application of an applied compressive load resulting in axial and lateral strain comparable to experimental uniaxial tests. We use initial material properties approximating a host material of a low-porosity basalt, and allow the material properties to evolve naturally with the growth of crack damage in the host volume. We introduce two failure criteria within the models; tensile and Mohr-Coulomb. Pore geometry variation as a function of the aspect ratio produces an order of magnitude variation in the material stiffness and ultimate strength. Materials containing flat pores (i.e.,  $c \parallel \sigma_1$ ) results in a marked weakening and reduction in Young's Modulus  $E$ . In cases where  $c \perp \sigma_1$ , materials are stronger and stiffer than isotropic ( $c = a$ ) tests. Failure mode and distribution is dependent on pore aspect ratio and orientation, and the proximity of adjacent pores. The pore fabric tensor 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.



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## **Faulting in travertine: experimental and outcrop analysis of heterogeneity and velocity anisotropy**

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Unlike established concepts of fault and fluid flow models within clastic rocks, the heterogeneous nature of carbonates means that faulting within these deposits is difficult to model and predict. In particular, understanding continental carbonate deposits is of increasing importance due to their great hydrocarbon reservoir potential, particularly with the development of continental carbonate plays within the 'pre-salt' of the South Atlantic. The nature of faulting within these continental-type carbonates and its impact on fluid flow is therefore crucial when considering reservoir characterisation and quality. To this end, we have carried out an integrated petrophysical and geomechanical study of shallowly buried Pleistocene travertine samples from central Italy. The study aims to understand the control heterogeneities have on the failure mechanisms and failure mode to ultimately understand the impact on fluid flow. Detailed petrophysical testing integrated with velocity analysis has also been used to assess the potential of using velocity responses as a predictive tool to identify fault related conduits (dilatational deformation) or barriers (compactional deformation) in the sub surface.

Travertine deposits form in a number of depositional settings producing various morphologies ranging from extensive depression depositional travertines to localised fissure ridge and mound deposits. Changes of facies within these deposits occur over millimetre to metre scales and are dependant on the depositional environment (i.e. hydrodynamic setting, surface topography, microbial community etc). Samples are predominantly composed of interbedded layers of different facies types (ranging from relatively low porosity crystalline dendrite cementstones to high porosity bubble boundstones) which results in a highly anisotropic medium whereby bedding parallel permeability can be up to two orders of magnitude higher than bedding-perpendicular permeability. The inherent variability in petrophysical properties of these facies creates a significant strength contrast between layers which will influence the process and geometry of brittle deformation.

Outcrop observations of travertine illustrates that deformation (faulting and fracturing) appears to be predominantly dilatational, likely due to early cementation and shallow burial at time of deformation. Triaxial testing of samples under reservoir conditions also result in dilatational deformation inferring this as the most significant mode of failure. Faulting is observed to have a stair-step morphology, following weaknesses in the sample which is controlled by the pore network architecture. It is therefore found that layering of high porosity facies control failure plane nucleation and architecture which results in complex and heterogeneous faulting reflecting the heterogeneities associated with the host rock facies. Ultrasonic velocity measurements were also carried out during multi-stage triaxial tests on samples to observe the effect of failure on velocity. Results indicate that experimentally induced dilatational deformation at high differential pressures is observed to cause significant decrease in P- and S-wave velocities. Significant localised velocity decreases may therefore indicate the presence of dilatational fluid conduits within travertine deposits in certain environments. The ubiquity of dilatational fractures intrinsic to travertines relates to their depositional process and setting and could present significant fluid permeability if open under subsurface conditions. As a result, the data in this study provides valuable analogues for this rarely studied lithofacies.

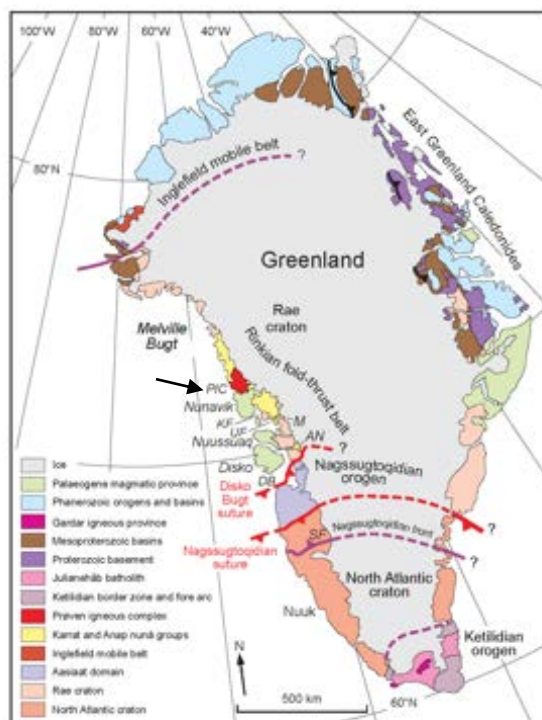
## Tectonic evolution of the Prøven Igneous complex, West Greenland: Investigation of Paleoproterozoic accretion processes using 3D photogrammetry

Sleath, P.R.<sup>1</sup>, McCaffrey, K.J.W<sup>1</sup>, Grocott, J.<sup>1</sup>, Kokfelt, T.F.<sup>2</sup>, Holdsworth, R.E.<sup>1</sup>, Sørensen, E.V.<sup>2</sup>

<sup>1</sup> Department of Earth Sciences, Durham University

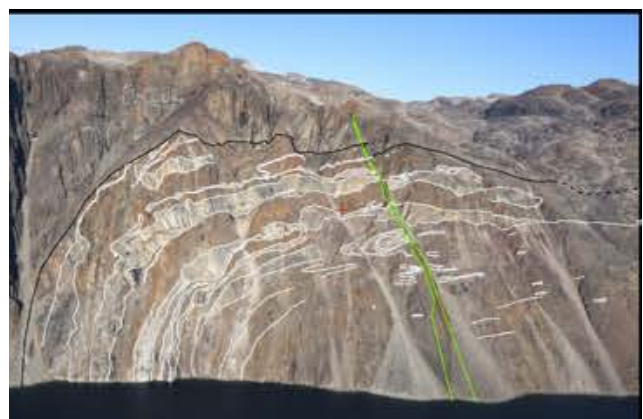
<sup>2</sup> Geological Survey of Denmark and Greenland (GEUS)

The Rinkian fold-thrust belt in West Greenland 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. 1.87 Ga. The area affected by the Rinkian fold-thrust belt includes the Prøven Igneous Complex, a ca. 90 x 80 km large intrusive complex of orthopyroxene-bearing monzogranite to quartz monzonite, which was intruded synchronously with high grade events at ca 1.87 Ga. Recent U-Pb zircon dating suggests the complex is some 30 Ma older at around 1.9 Ga. These new dates have spurred an effort to reinvestigate the Prøven Igneous Complex in terms of its tectonic setting and position within the evolutionary sequence of the Rinkian fold-thrust belt. The area is cut by a series of well exposed and deeply incised fjords but is a harsh, remote and difficult to access landscape. In the summer of 2018, over 16,000 aerial photos of the Prøven district in West Greenland were collected by GEUS during a week of fieldwork in the area. Stereo photogrammetry was used to produce 3D models of the structures exposed in the steep cliffs, allowing an analysis of the area to be carried out using *3D Stereo Blend* at the Photogeological Laboratory in Copenhagen. A lithostratigraphic scheme based on the original mapping of the complex that includes contacts within the igneous complex and the underlying paragneisses has been tested as a mechanism to produce detailed geological maps and cross sections. Structural analysis of contact and fabric geometries in well exposed areas, verified with structural data from outcrops visited to ground-truth interpretations, has provided new insights into the deformation history of the Prøven Igneous Complex and the tectonic setting for the Rinkian fold-thrust belt overall.



<Fig 1: The main geological provinces and boundaries of Greenland.

PIC = Prøven Igneous Complex



^Fig 2: Tectonic interpretation of large scale antiform in paragneiss intruded by leucocratic granite dykes on the east coast of Nutaarmiut island, Prøven district.

## **The tectonic history and structural characterisation of SW England NW-SE fault zones for deep geothermal energy**

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The high heat flow associated with elevated U, Th and K contents of the Early Permian Cornubian Batholith mean SW England is one of the most prospective areas in the UK for deep geothermal energy exploration. The UK's deepest onshore borehole (UD-1, 5057 m TVD) was completed in 2019 at the United Downs Deep Geothermal Energy Power Project in Cornwall where it intersects a granite-hosted segment of the NW-SE striking Porthtowan Fault Zone. A NW-SE fault zone, the 'Great Cross-course' is also being targeted in 2020 by Eden Geothermal Ltd at a depth of c. 4500 m.

Steeply-dipping NW-SE fault zones are well-known throughout SW England and commonly have trace lengths exceeding >10 km. They are being targeted as deep geothermal reservoirs due to a perceived higher permeability than the surrounding granite and a favourable parallelism, or slight obliquity, with the maximum horizontal stress ( $\sigma_H$ ). The onshore expression of these fault zones is reasonably well-known from a combination of classical field mapping and metal mining, but the latter data are typically restricted to within 300 m of surface (two mines to 1000 m). The post-Carboniferous structural evolution of these faults is less well-constrained. Reactivation in the Permian, Triassic and late Jurassic-Cretaceous has been documented and the Sticklepath-Lustleigh Fault Zone in Devon has developed mid-Cenozoic strike-slip basins.

The purpose of this work is to combine remote-sensed and historical data, including that from offshore sedimentary basins, with new field data to generate improved model(s) for the tectonic and structural evolution of these fault zones that addresses their: (1) distribution, (2) geometry, kinematics and relative chronology.

A new regional lineament map for SW England has been derived from high-resolution airborne magnetic, radiometrics and LiDAR data from the Tellus South West survey. By integrating multiple datasets from different types of spatial data, a comprehensive, composite lineament network has been created which consistently represents fault zones at the regional scale. Geological lineaments are used as a proxy to map fault zones, especially within granite areas, which may be prospective for geothermal energy. This lineament map is used to interpret the distribution and geometry of fault zones onshore at the decimetre to kilometre scale.

Additionally, we present modern structural mapping and data collection from the newly identified Land's End-Porthgwarra Fault Zone which is considered to be a field analogue for NW-SE fault zones and their post-Variscan tectonic history. Outcrop scale data is combined with regional analysis of both onshore and offshore datasets to map the strike extent of fault zones and identify areas where later structures may interact with the main NW-SE fault zones to either increase, or decrease, potential permeability.

The models generated through this work will feed into target generation for future geothermal resources in SW England. This work forms part of a work package within the NERC-funded GWatt (Geothermal Power Generated from UK Granites) Project.

***“Global characterisation of passive margin architecture: A revised approach with insights from potential fields data along the West African Margin”***

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Passive margins are commonly categorised into two end-member models based on the amount of magma produced during continental rifting and breakup, resulting in ‘magma-rich margins’, or ‘magma-poor margins’ as a generic classification. This broad classification may not reflect the internal variations present, both locally within one passive margin, and globally when considering the entire conjugate system. In fact, variations in the architecture of both magma-poor and magma-rich margins are very common when considering the potential occurrence of hyperextended continental crust, exhumed mantle, or seaward dipping reflections. It is within the transition zone between continental and oceanic crust that much uncertainty in our interpretations of rifted margins exists. Combining seismic and potential fields data should reduce this uncertainty by deriving a suite of global architectures and a robust, unbiased workflow to attempt to address the varying degrees of interpretative uncertainty within such data sets.

This contribution focuses on an example from West Africa, where we use seismic and potential field data to characterise the signature of the different crustal types and highlight insights into both local and regional variations of these architectures. The aim is to propose a revised classification of rifted margins that captures the inherent variability observed, focusing on observations of crustal type (relying on seismic facies, potential fields signature) rather than process driven characterisation. This approach should reduce uncertainty when exploring data-poor, frontier-style margins.

## Thermal liability of hyaloclastite in the Krafla geothermal reservoir, Iceland: the impact of phyllosilicates on permeability and rock strength

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Keywords: Krafla, basaltic hyaloclastite, thermal stress, smectite, mechanical properties, geothermal, clay mineralogy

### **Abstract**

Geothermal fields are prone to temperature fluctuations from natural hydrothermal activity, anthropogenic drilling practices, and magmatic intrusions. These fluctuations may elicit a response from the rocks in terms of their permeability, mineralogical and mechanical properties. Hyaloclastites are a highly variable volcanoclastic rock predominantly formed of glass clasts that are produced during non-explosive quench-induced fragmentation, in both subaqueous and subglacial eruptive environments. They are common in high latitude geothermal fields as both weak, highly permeable reservoir rocks and compacted impermeable cap rocks. Basaltic glass is altered through interactions with external water into a clay-dominated matrix, termed palagonite, that acts to cement the bulk rock. The abundant, hydrous phyllosilicate minerals within the palagonite can dehydrate at elevated temperatures, potentially resulting in thermal liability of the bulk rock.

Using surficial samples collected from Krafla, northeast Iceland, and a range of petrographic, mineralogical and mechanical analysis, we find that smectite dehydration occurs at temperatures commonly experienced within geothermal fields. Dehydration events at 130, 185 and 600 °C result in mass loss and progressive contraction. This evolution results in a positive correlation between treatment temperature, porosity and permeability gain. Gas permeability measured at 1 MPa confining pressure shows a 3-fold increase following thermal treatment at 600 °C. Furthermore, strength measurements show that brittle failure is dependent on porosity and therefore the degree of thermal treatment. Following thermal treatment at 600 °C, the indirect tensile strength, uniaxial compressive strength and triaxial compressive strength (at 5 MPa confining pressure) decrease by up to 68% (1.1 MPa), 63% (7.3 MPa) and 25% (7.9 MPa), respectively. These results are compared with hyaloclastite taken from several depths within the Krafla reservoir, through which the palagonite transitions from smectite to chlorite-dominated.

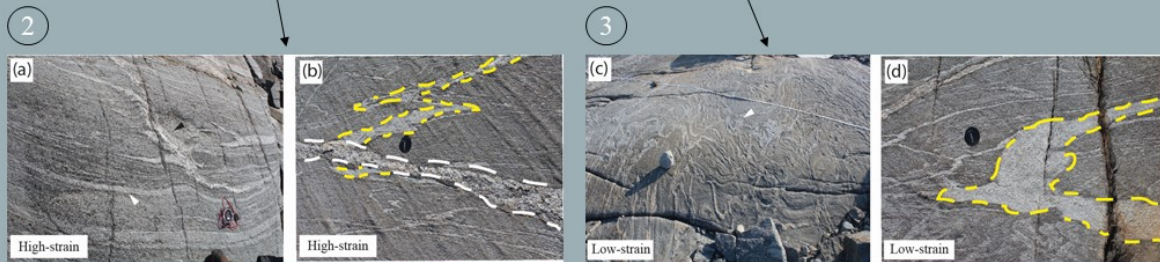
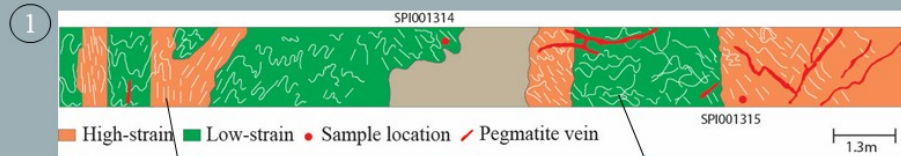
We discuss how temperature-induced changes to the geomechanical properties of hyaloclastite may impact fluid flow in hydrothermal reservoirs and consider the potential implications for hyaloclastite-hosted intrusions. Ultimately, we show that phyllosilicate-bearing rocks are susceptible to temperature fluctuations in geothermal fields.

# Feedback between melt migration and deformation: a case study on the lower crustal section of Akia terrane, SW Greenland

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The close spatial and temporal relationship between high temperature rocks, crustal scale shear zone and plutons can be observed in active continental settings (Brown, 1995; Collins & Sawyer, 1996), but their interdependence is still debated.



- High strain:**
1. Overall felsic appearance
  2. Closely spaced felsic bands  $\parallel$  foliation
  3. Tight 'M' type isoclinal folds
  4. 30-35 veins/m<sup>2</sup>

- Low strain:**
1. Overall mafic appearance
  2. Felsic bands at an angle to foliation
  3. Open asymmetrical folds
  4. 15-20 veins/m<sup>2</sup>

## **The rock record of the earthquake cycle**

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During the earthquake cycle, faults typically experience rapid weakening and seismic slip followed by a postseismic period with various slip behaviours, and an interseismic interval during which the fault is locked. These different intervals are characterised by different frictional states and physical mechanisms that impart microstructural evidence in the rock record. A key part of the earthquake cycle is the transition from very weak during the earthquake, to strong enough to accrue stress that ultimately builds to a subsequent earthquake. In this presentation, we will put microstructural observations from several active faults from the central Italian Apennines in the context of host fault geological and Quaternary activity. The central Apennines have undergone extension since 2-3 Ma on a complex and evolving network of carbonate normal faults. Well-preserved fault scarps have been exposed by earthquakes over the Holocene, and they record the rate and pattern of earthquake slip. We can also infer the depth represented by the exposed scarp based on the total vertical displacement over the fault's lifespan.

We classify faults based on their long-term behaviour as juvenile, adolescent, or mature in order to compare microstructures between different stages in fault development. We will show observations from optical microscopy (including under cathodoluminescence), and measurements of crystal orientation quantified using electron back scatter diffraction (EBSD) and neutron diffraction texture analyses. EBSD analyses suggest that the crystallographic preferred orientation (CPO) strengthens with fault maturity, and that crystal plastic deformation is an important deformation mechanism even at relatively shallow levels (and low ambient temperatures) on faults. New results from neutron diffraction analyses will give insight into the deformation behaviour at much finer grain scales found in the fault matrix and along slip surfaces. These results give insight into the rheology of faults throughout the earthquake cycle, which is crucial for understanding how the state of stress evolves through time.