TSG Tectonic Studies Group

VISTA

The Tectonic Studies Group Annual General Meeting

14 - 16 January, 2019
University of Bergen

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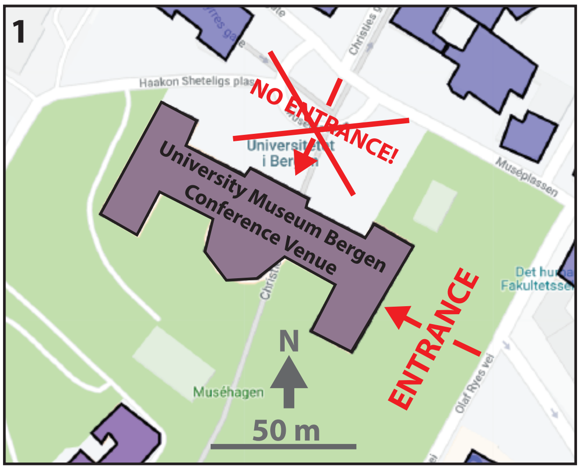
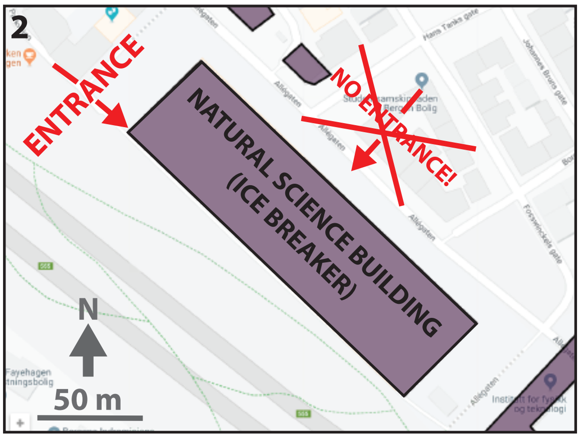
Key sites for TSG AGM 2019 Bergen

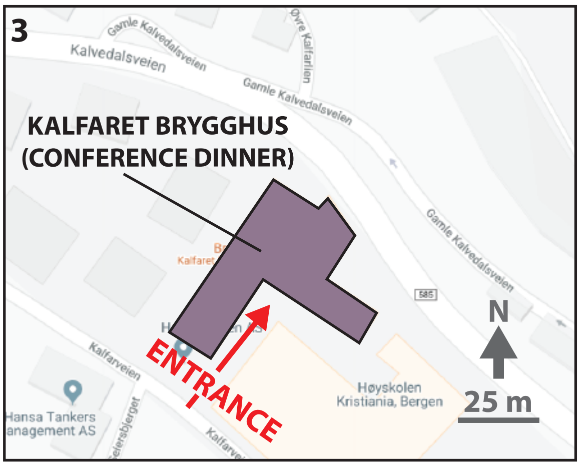
1. Conference venue:
Aula at the University Museum Bergen
Registration at the ground floor (enter from the botanical gardens below the mezzanine).
Address: Muséplassen 3



2. Iceabreaker
The student bar *Integrerbar* is on the 1st floor of the Natural Science building ("Realfagbygget").
Use the entrance from the northwestern corner of the building.
Address: Allégaten 41



3. Conference dinner
Kalfaret Brygghus
Address: Kalfarveien 76
Coach will depart from (X)Festplassen at 18:45 on Tuesday 15th. Coaches will be marked with the TSG logo and #TSG2019



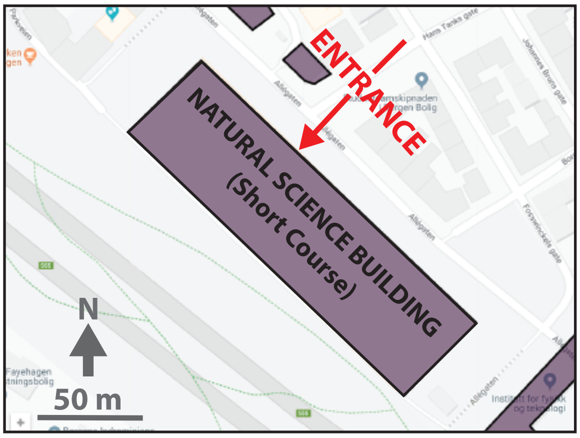
Short course

Sunday 13th January

12:30 - 18:00

Short-course 1: Seismic interpretation; application to structural geology and potential pitfalls
Professor Christopher Aiden-Lee Jackson (Imperial College, London) and
Dr. Clare Bond (University of Aberdeen)

Short-course 2: Fracture network topology analysis in Network GT
Dr. Bjørn Nyberg and Dr. Casey Nixon (University of Bergen)



Short course venue:
Both shortcourses will be on the 2nd floor of the Natural Science building ("Realfagbygget"). Use the entrance from the northeastern long-side of the building.

Registration at the ground floor inside the main entrance.

Address: Allégaten 41

Conference information

Conference venue

The TSG 2019 meeting will take place in the university aula. (https://www.uib.no/universitetsaulaen - Norwegian only) at the Natural History Museum (https://www.uib.no/en/universitymuseum), where all conferences sessions will take place.

Registration and Information Desk

All delegates are required to register at the Natural History Museum. The Registration and Information Desk will be available Monday 14th of January from 08:30 – 14:00. After this it will be possible to register upstairs in the aula (contact the committee or student helpers – will be wearing TSG-t-shirts.

Free Wi-Fi at campus

Free Wi-Fi is available through most of the campus. '*Eduroam*' is available for guest coming from institutions that are members of the eduroam-cooperation. For other guests '*uib-guest'* is available (fill in phone number (remember +country code) under "Username/Phonenumber" and click send, you will then receive a password that you fill in under 'Password:') Ask student helpers if any trouble with connecting.

Oral presentations

Speakers are expected to speak for 12 minutes, with a further 3 minutes for questions. Keynote speakers are expected to speak for 40 minutes, with a further 5 minutes for questions.

Poster presentations

Posters will be displayed for the duration of the meeting. Please use your designated numbered board. All posters should be A0 and in portrait. Presenters are required to stand by their posters at the times indicated in the programme (14:45-15-:45 Monday and Tuesday).

Access

There are toilets and disabled toilets in the Natural History Museum.

No Smoking!

Smoking in Norway is banned indoors in public buildings and on public transport. It is also illegal to smoke in outdoor locations that are close to schools and hospitals.

The University of Bergen

The University of Bergen (UiB) is an internationally recognised research university. Academic diversity and high quality are fundamental for us. UiB is the most cited university in Norway.There are seven faculties at UiB and there are a total of 16 900 students at the university. Around 1 880 of these are international students. We employ 3 600 staff. PhD candidates are paid employees of staff, making the doctoral degree at UiB particularly attractive for rising talent. About one in three graduating doctors are from outside Norway. Find more information at www.uib.no.

The department of Earth Science – UIB

The Department of Earth Science (GEO)'s overall goal is to develop new knowledge of the Earth's structure, evolution and dynamics. The department is organised into four thematic groups: Geodynamics, Basin and Reservoir Studies, Geochemistry & Geobiology, and Quaternary Earth Systems. The Department of Earth Science offers a broad earth science education, offering BSc, MSc and PhD educational programmes. The department has 37 permanent faculty employees and more than 110 research positions and 34 technical/administrative positions. Our employees are from more than 30 different countries. The department is partner in additional three research centres: The Bjerknes Centre for Climate Research, The Centre for Integrated Petroleum Research and K.G. Jebsen Centre for Deep Sea Research. Find more information at www.uib.no/en/geo.

General information about visiting Bergen

General advice for UK visitors to Norway can be found on the UK Government website (https://www.gov.uk/foreign-travel-advice/norway).

Weather

Bergen can be wet (rain and snow) and cold (around 0°C) in January, so please bring appropriate clothes and footwear. A generally reliable weather forecast is available at https://www.yr.no/place/Norway/Hordaland/Bergen/Bergen/.

Local transport

The simplest way to get between the Airport and the city centre is by the light railway ("Bybanen"). It costs 37 NOK one-way (a ticket lasts for 90 minutes), and tickets can be bought using cash or cards are the stations (https://www.skyss.no/en/timetable-and-maps/bergen-light-rail/). The journey takes about 45 minutes, with services every 7 to 20 minutes, reducing in frequency at night). Check the schedule before travelling at night. You could also travel between the Airport and the city centre by coach ("Flybussen"), which is a bit quicker but more expensive (https://www.flybussen.no/billett/#/reise/til/bergen-flyplass/bgo). Taxis are available but are expensive by global standards. Bergen Taxis are one of the largest local companies (http://www.bergentaxi.no/english, telephone 07000), who claim that the maximum fare between the Airport and the city centre for 1-4 people at the weekend or evening is 500 NOK (http://www.bergentaxi.no/english/airport-shuttle).

Car parking

Parking can be problematic around the University, but car parks are available. For information, see https://en.visitbergen.com/visitor-information/travel-information/getting-here/to-bergen-by-car/car-parking-and-car-parks.

Cash machine and spending

The local currency is the Norwegian kroner (NOK). There are cash machines at various banks in town. In Norway, however, it is usual to pay for everything using a debit or credit card. The exchange rates (start January 2019) are £1 ~ 11 NOK, €1 ~ 9.2 NOK.

Prices in Norway are famously high, especially for food and alcohol (https://www.numbeo.com/cost-of-living/in/Bergen). Notice how people swarm the Duty Free shop at the Airport. You may well regret the generosity of buying a round of drinks.

Health and emergency services

For emergency medical assistance, dial 113. For a police emergency, dial 112. For medical problems, visit the Bergen Accident and Emergency Department ("Legevakt"), which is at Solheimsgaten 9, approximately 1.5 km SE of the Natural History Museum. It is open 24 hours a day (telephone + 47 55568760). Remember to bring your European Health Insurance card, just in case (https://helsenorge.no/foreigners-in-norway/who-is-entitled-to-a-european-health-insurance-card).

Things to see and do

If you have free time, it is worth seeing the sights in and around Bergen. Contact the Bergen Tourist Information Centre (https://en.visitbergen.com/visitor-information/bergen-tourist-information) for full information and advice. Sadly, Bergen Leprosy Museum is closed until 15th May 2019, but here are some other suggestions:

1. The historic buildings of Bryggen are a popular attraction in the city centre. Bryggen is on UNESCO's World Heritage List (https://en.visitbergen.com/things-to-do/bryggen-in-bergen-p878553).
2. To get a ride on a funicular to get an overview of Bergen, try Floibanen (https://en.visitbergen.com/things-to-do/floibanen-funicular-p822813).
3. If you have a day free and fancy seeing a fjord and the mountains, try "Norway in a Nutshell" (https://en.visitbergen.com/things-to-do/norway-in-a-nutshell-r-p825223).

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TSG 2019 - Oral Programme

Monday 14th January

09:30 - Registration and Welcome Refreshment

10:30 - Welcome and opening statement - Atle Rotevatn/Karen Mair/Anette Tvedt

Session:	**Fault Growth and Fracture Networks**		**Chair: Karen Mair**
1045		Life Cycle of a Fault: New insight into interseismic healing cycles	Oliver Campbell
1100		Conjugate relay zones; geometry of displacement transfer between opposed-dipping normal faults	Robert Worthington
1115		Bedrock fracturing of southern Finland - characteristics and prediction at different scales	Nicklas Nordbäck
1130		Lower-Carboniferous to Cenozoic deformation in the Irish Midlands, insights from integrated geological and geophysical modelling	John Conneally
1145	**KEYNOTE:**	**Fault-based PSHA, fault growth and interaction, and fault scaling relationships – the need for detailed primary data**	**Joanna Faure-Walker**

12:30-13:30 - Lunch

Session:	**Fault Growth and Fracture Networks**		**Chair: Karen Mair**
1330		How do we see fracture networks? The role of subjective bias in fracture data collection.	Billy Andrews*
Session:	**Rifts, Basins and Passive Margins**		**Chair: Zoe Mildon**
1345		Fluid circulation and fault-controlled diagenesis along a major syn-rift border fault system – the Dombjerg Fault and the Wollaston Forland Basin, NE Greenland	Eric Salomon
1400		How do variably striking normal faults reactivate during rifting? Insights from southern Malawi	Jack Williams
1415		Structural inheritance in the Labrador Sea/Baffin Bay rift systems: Is the control by pre-existing crustal or mantle structures?	Ken McCaffrey
1430		Simultaneous Extension and Contraction Facilitated by Strike-Slip Faults in the Phitsanulok Basin, Central Thailand	Sarawute Chantraprasert

14:45 - Poster Session and Refreshment

Session:	**Rifts, Basins and Passive Margins**		**Chair: Clare Bond**
1545	**KEYNOTE:**	**A Greenland centered puzzle: Updated plate reconstructions of the North Atlantic and Arctic**	**Grace Shephard**
1630		Structural inheritance in multi-phase rifts: Examples from the northern North Sea rift	Thomas Phillips
1645		Structural and geodynamic modelling of the influence of granite bodies during lithospheric extension: application to the Carboniferous basins of Northern England	Louis Howell
1700		On fault growth and bulk constriction in transtensional supradetachment basins	Per Terje Osmundsen
1715		Controls on the late Neogene transition from marine to terrestrial deposition in the Central Myanmar Basin	Seehapol Utitsan*

17:30 - Icebreaker
(*Integrerbar* at the Natural Science Building)

Tuesday 15th January

Session:	Fault Zones and Fluid Flow I		Chair: Jessica McBeck
0900		Deformation mechanisms, structural diagenesis, and petrophysical properties of calcite- and dolomite-rich fault rocks	Francesco Ferraro*
0915		Structural controls of fault-zone fluid flow, and hydraulic connectivity between active border faults and rift basins: constraints from the Bwamba Fault, East African rift.	Allan Hollinsworth*
0930		Fault Void Fills: Pervasive and persistent fluid flow pathways in fractured crystalline and carbonate reservoirs	Kit Hardman*
0945	**KEYNOTE:**	**A multidisciplinary approach to unravel fluid circulation and tectonic evolution within shallow crustal potentially seismogenic fault zones**	**Luca Smeraglia**

10:30 - Coffee/Tea Break

Session:	Magmatism and Intrusions		Chair: Sian Evans
1100		Variation in style of magmatism and emplacement mechanism induced by changes in basin environments and stress fields (Pannonian Basin, Central Europe)	Attila Petrik
1115		Transient thermal effects in sedimentary basins with normal faults and magmatic sill intrusions – A sensitivity study	Magnhild Sydnes*
1130		Igneous intrusion segments as a record of intrusive sheet growth and emplacement mechanisms?	Richard Walker
1145		Tectonic controls on Taupo Volcanic Zone geothermal expression	David McNamara
1200		How do normal faults grow above dykes?	Craig Magee
1215		Stress state versus host-rock lithology as a control on architecture of igneous sheet intrusions	Christian Eide

12:30-13:30 - Lunch

Session:	Salt Tectonics		Chair: Craig Magee
1330		The Structure and Responses of Carbonate Sediments To Salt Tectonics: New Insights from 3D Seismic and Outcrop Analogues	Gregoire Messager
1345		Intrasalt Structure And Strain Partitioning In Layered Evaporites: Insights From The Messinian Salt In The Eastern Mediterranean	Sian Evans
1400		Structural Style of Early Stage Salt Tectonics: insights from 3D Seismic Data, offshore Angola	Aurio Erdi*
1415		The importance of basement configuration on the development of salt structures in confined salt-related basins: insights from analogue modelling	Luis Alberto Rojo Moraleda*
1430		Growth and inversion of a salt-rich oblique rifted margin, eastern North Pyrenees	Mary Ford

14:45 - Poster Session and Refreshment

Session:	Active Tectonics and Seismic Hazard		Chair: Jack Williams
1545	**KEYNOTE:**	**Untangling subduction interface and upper plate fault coastal deformation signatures to constrain the seismic hazard of the Hikurangi subduction margin, New Zealand**	**Kate Clark**
1630		Time dependant seismic hazard developments using Coulomb stress changes	Zoe Mildon
1645		Neotectonic fault reactivation and landscape rejuvenation on Norway's post-glacial rifted margin	Tim Redfield
1700		The ~25 ka paleoseismic sedimentary record of the Central Corinth Rift	Gino De Gelder

19:00 - Conference Dinner
(*Kalfaret Brygghus* - Coach from *Festplassen* at 18:45)

Wednesday 16th January

Session:	Fault Zones and Fluid Flow II		Chair: Casey Nixon
0900		Fault damage clustering and fault surface initiation in porous sandstones	Roger Soliva
0915		3D geometry and architecture of a normal fault zone in poorly lithified sediments: A trench study on the Baza Fault, Spain	Ivan Medina-Cascales*
0930		Ripplocations: a new mechanism to explain the deformation of phyllosilicates	Joe Aslin*
0945	**KEYNOTE:**	**Dating faults by K-Ar illite/muscovite geochronology; approach, interpretations and challenges**	**Espen Torgersen**

10:30 - Coffee/Tea Break

Session:	Fault Zones and Fluid Flow II		Chair: Casey Nixon
1100		Coseismic ultramylonites: evidence of fault weakening by viscous flow during seismic slip.	Giacomo Pozzi*
1115		Microstructurally-controlled K-Ar geochronology across fault zones	Thomas Scheiber
Session:	**Orogenesis and lower crustal deformation**		**Chair: Thomas Philips**
1130		In-situ U-Pb ages of multiple generations of calcite related to the Ivriz Detachment, Central Anatolia	Derya Gürer
1145		Stress permutation during inversion events and the patchy development of structures in orogenic forelands	Enrico Tavernelli
1200		Accretionary processes at the northern Australian margin in NW New Guinea – A record of rapid and recent orogenesis	Max Webb*
1215		Deformation mechanisms in amphibolite-facies ultramylonites associated with pseudotachylytes	Simone Papa*

12:30-13:30 - Lunch & AGM

Session:	Orogenesis and lower crustal deformation		Chair: Espen Torgersen
1330		Ductile shear zones: windows into deformation of lower crust – case study from the Kynsikangas shear zone in SW Finland	Jon Engström
1345		Broadhaven revisited: a new look at models of fault-fold interaction	Adam Cawood*
1400		How complex structures affect thermal maturity indicators: a case study from the Haut Giffre, French Alps	Lauren Kedar*
1415		Structural reworking of the lower crust during Caledonian nappe emplacement in Arctic Norway	Alberto Ceccato
Session:	**Reservoirs and Resources: From exploration to storage**		**Chair: Thomas B. Kristensen**
1430		3-D structural uncertainty in seismic interpretation: A case study on the Gullfaks fault block	Alexander Schaaf*
1445		Structural controls on fault and top seal. Insights from analysis of column height data from the Snøhvit gas field in the Hammerfest Basin, SW Barents Sea	Isabel Edmundson*
1500		How do seismic survey parameters and artifacts effect the imaging of normal faults: a case study from the Snøhvit Field, Barents Sea	Jennifer Cunningham*

15:15 - Coffee/Tea Break

15:45 - Student Presentation Awards

Session:	Reservoirs and Resouces: from exploration to storage		Chair: Anette Tvedt
1600		The SAFARI database: a new way of sharing outcrop data	Nicole Naumann
1615		Fracture network characterization and two-dimensional connectivity in geothermal reservoir analogs: Multi-scale investigations from the Sotra Islands in Norway	Luisa Zuluaga
1630		Storage and migration properties of fractured carbonate reservoirs, insights from the analysis of surface structural analogs	Fabrizio Agosta
1645		Impact of faults on CO2 Storage Capacity and Leakage Risk Assessment: Key Learnings from Smeaheia, off-shore Norway	Long Wu

17:00 - Closing Remarks - Atle Rotevatn/Clare Bond

End of Conference

TSG 2019 - Poster Programme

Session:	**Fault growth and evolution**	Chair: Matteo Demurtas
101	Principal slip zone characterisation in natural basaltic faults	Bob Bamberg*
102	Controls on fault activation and slip along the Húsavík-Flatey transform fault, Northern Iceland	Alodie Bubeck
103	Does cleavage matter? Investigating the influence of cleavage planes during granular flow	Matteo Demurtas
104	Seismic forward modelling of carbonate hosted normal faults	Vilde Dimmen*
105	Failure mechanisms in travertine and the impact on acoustic properties	Dorothy Drayton*
106	How lithology, tectonic setting, and fault size control normal fault growth: Using a large global	Bailey Lathrop
107	Damage scaling and fault segmentation in carbonate rocks	Sylvain Mayolle*
108	The 1908 Mw 7.1 Messina Earthquake Italy revealed: 5m rupture of an offshore 70° east-dipping normal fault	Marco Meschis*
110	3-D complexity and imaging of crustal-scale normal faults – observations from the Vette Fault, northern North Sea	Thomas Phillips
111	The Lærdal-Gjende fault (southwestern Norway): A new, high resolution, combined structural-geochronological study	Giulia Tartaglia*
112	A Test of Fault Growth Models Using 3D Seismic Reflection Data from Offshore Angola	David Redpath*
113	How do normal faults grow?	Atle Rotevatn
Session:	**Faults, fractures and fluid flow**	Chair: Luisa Zuluaga
201	Using U-Pb calcite geochronology to constrain the timing of fracturing and fluid-flow in Jurassic	Jack Lee*
202	The effect of fluid pressure and composition on hydrothermal vein precipitation rate, permeability and microstructure	Steven Beynon*
203	Casualties of War: Microstructural damage to stone heritage by ballistic impacts	Oliver Campbell*
204	Permeability reduction by cataclastic deformation bands in mixed aeolian-fluvial facies	Karl Clark*
205	Percolating force chains and propagating fractures in sandstone	Jessica McBeck
206	The Use of GIS in the Spatial, Geometric and Topological Analysis of Fracture Networks:	Björn Nyberg
207	Igneous sill geometry as a record of tectonic horizontal compression	Tara Stephens*
208	Lithon morphology and change in carbonate elastic properties in a regional fault zone	Onyedika Anthony Igbokwe*
Session:	**Georesources**	Chair: Isabel Edmundson
301	Geomechanical and Petrological Characterisation of North Sea Reservoir and Caprock	Michael Allen
302	Permeability reduction from porosity occlusion due to CO2 - rock interaction: implications for	Clare Bond
303	Microstructural and Physiochemical Processes Influencing Fracture Sealing in Geothermal	Aisling Scully*
304	Structural controls on the geometry of the Curraghinalt gold deposit, Northern Ireland:	James Shaw*
305	Fracture corridors and low offset faults in basement rocks, what are the impact on basement and geothermal reservoir performance?	Eivind Bastesen
306	Using Variscan Metasediments as an EGS Reservoir on a European Scale – Preliminary Stages of Outcrop Analogue Characterisation	Katherine Ford*

Session:	**Orogenesis and lower crustal deformation**	Chair: Grace Shephard
401	Ductile structures in basement windows of the SW Scandinavian Caledonides and their potential for brittle reactivation	Johannes Wiest*
402	Unravelling the relationship between thrust and sinistral shear in the Shetland Caledonides	Timothy Armitage*
403	Review of proposed Ord Window structures: thinking in three dimensions	Rebecca Macaskill-Robertson*
404	Single Grain Orientation Analysis on Dauphiné twins in vein-quartz in slates (Ardennes, Eifel)	Alexander Minor*
405	Asymmetric continental deformation along the South Atlantic and its influence on Large	Eric Salomon
406	Dyke reactivation across the frictional-viscous transition: Insights from Precambrian	Laura Scott*
407	A revised palaeogeography of the Falkland Islands microplate based on offshore seismic and gravity data	Roxana Stanca*
408	Intraplate deformation offshore North Sumatra: New Insights from integration of IODP Expedition 362 results with seismic data	Duncan Stevens*
Session:	**Rifts and basins**	Chair: Alodie Bubeck
501	Cenozoic kinematics of the seismically active western continental margin of the Indian plate	Mohamedharoon Shaikh*
502	Middle Jurassic and Early Cretaceous rifting events in the South-East of the Mesopotamian Basin, South-East Iraq: evidence from subsidence analysis	Layth Al-Madhachi*
503	Formation of intracontinental sag basin: West Siberia basin	Adam Cheng
504	A combined modelling approach to plate vector rotation in rift-transform intersections.	Ken McCaffrey (Georigios Pavlos Farangitakis*)
505	Fault Reactivation in the Southern North Falkland Basin: Complex Tectonic History or Partitioned Transtension?	Dave McCarthy
506	Deformation band formation in function of progressive burial: depth calibration and	Attila Petrik
507	Fingerprinting structural inheritance - Its styles and expressions in rift systems	Thomas Phillips
508	Fold growth in the South Caspian Sea Basin: Mechanisms and interaction with deep-water lacustrine sediments	Andrew Procter*
509	Fault reactivation and superimposed basin development: onshore insights from the Inner Moray Firth Basin, Scotland	Alexandra Tamas*
510	Strain Modification in Oblique Rift Settings: Evolution of the Late Jurassic Lomre-/Uer Terraces, North Sea Rift	Fabian Tillmans*
511	Multiphase rifting controlled by pre-existing basement structures: A case study of the Utsira High, South Viking Graben, North Sea Rift, offshore Norway.	Thomas Berg Kristensen
512	A comparative analysis of rift faulting and underlying domal basement reflections at the Frøya High, offshore Mid-Norway	Jhon Muñoz-Barrera*
513	The evolution of normal fault arrays in a rift basin: example from the Thebe field, NW Australia	Sophie Pan*
Session:	**Salt tectonics**	Chair: Isabel Edmundson
601	Influence of salt tectonics on the subalpine chains of SE France; from Tethyan rifting through to Alpine compression	Samuel Brooke-Barnett*
602	The effects of salt tectonics in the evolution of a fold and thrust belt, Southern Subalpine Chains, France	Lajos Adam Csicsek*
603	Extension initiation and localization on minibasin formation in passive margin salt basins	Zhiyuan Ge

Oral presentation abstracts

Life Cycle of a Fault: New insight into interseismic healing cycles

O. Campbell[1,2], L.Gregory[2], S.Piazolo[2]

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[2]School of Earth and Environment, University of Leeds, Leeds, England
campbellor@cardiff.ac.uk

Fault surfaces are planes of weakness, yet seismic events can repeatedly occur along their length. The processes by which these failure surfaces strengthen, and subsequently accrue sufficient stress to produce a seismic event upon failure, is paramount to furthering our understanding of the seismic cycle. By using fault length as a proxy for its maturity, we compare fault plane microstructures across a series of active carbonate normal faults in the Italian Apennines, ultimately proposing a relationship between a fault's maturity and the microstructures observed. Cathodoluminescence reveals events of fracture-healing within breccia clasts that are not visible using conventional optical methods. This observation demonstrates fracture-healing plays a major role in "repairing" bulk rock strength. Quantitative orientation data from electron back scatter diffraction (EBSD) provides evidence of crystal plasticity and ductile deformation mechanisms, with some grains exhibiting internal misorientations of 12°. This progressive orientation change cannot be the direct result of the brittle deformation during fault rupture, but instead may be a response to high stress imposed from multiple phases of fault activity. The longer the faults, and thus the more mature, the less the record of fracture-healing events, internal misorientation and ductile deformation is preserved. Grain size reduction tends to be so advanced in these faults that internal deformation cannot be documented. Conversely, the juvenile faults have experienced much less grain size reduction, and so retain a more complete record of fracture-healing and underlying mechanisms.

Conjugate relay zones; geometry of displacement transfer between opposed-dipping normal faults

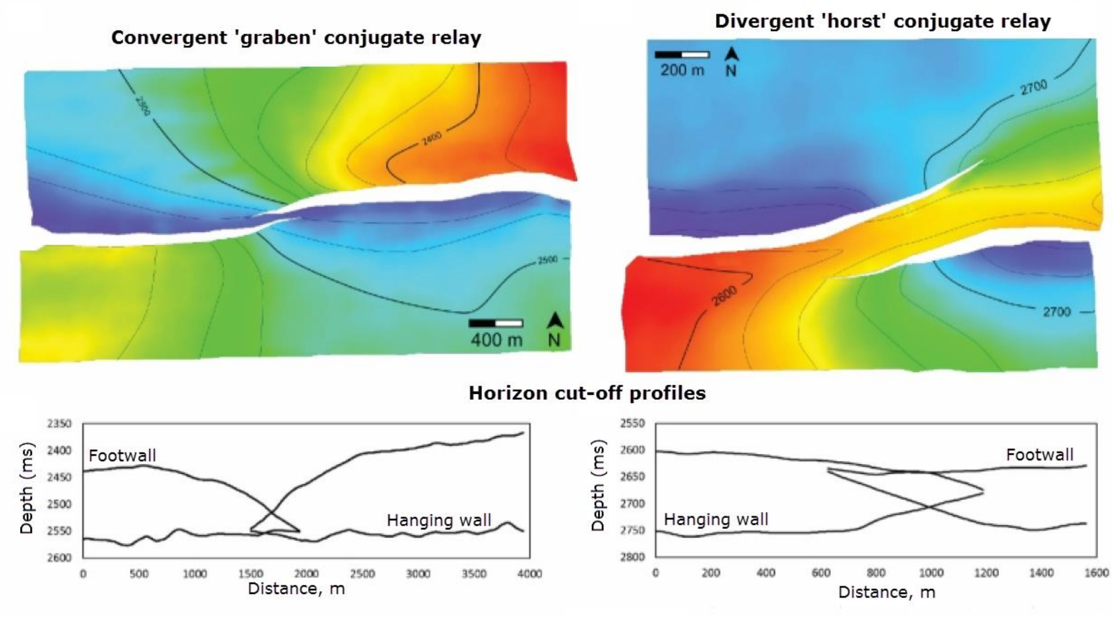
R. Worthington[1], C. Childs[2], J. Walsh[2], and V. Roche[2]

[1]Equinor AS, Bergen, Norway.
[2]Fault Analysis Group, UCD School of Earth Sciences, University College Dublin, Ireland.
rpw@equinor.com

Overlapping opposed dipping normal faults can have complementary displacement distributions, indicating transfer of displacement between them in the same way as at relay zones between faults with the same dip direction. We constrain the mechanism by which displacement is transferred between opposed dipping faults by examining the geometries of faulted horizons and fault throw distributions at these conjugate relay zones.

Structure contour maps of horizons offset by overlapping opposed dipping faults from different extensional settings display a consistent pattern. Above the line of intersection between the conjugate faults the deformed horizon is flat between converging faults and displacement transfer is reflected in changes in footwall elevation. Below the line of fault intersection the mutual footwall is flat and elevation changes occur in the hanging walls of the divergent faults. These elevation changes can be explained as a simple superposition of the deformation fields of two faults that have retarded lateral propagation due to the presence of the other synchronous fault, irrespective of whether the two faults actually intersect.

The patterns of horizon elevation strongly resemble those seen at boundaries between adjacent basin-scale half-graben of opposed polarity. As we have come to realise from detailed studies of such larger scale structures, transfer faults linking overlapping faults seem absent. For the cases examined here, we also observe no physical linkage except in map view when horizons are inclined and cross the line of fault intersection. Further, we note local strike changes where fault tips turn slightly inwards towards their hanging walls. Linkage and geometry between opposed dipping faults may often be wrongly interpreted in subsurface data, with implications in the industry for reservoir drainage and injection strategies.



Bedrock fracturing of southern Finland - characteristics and prediction at different scales

N. Nordbäck[1], J. Mattila[1], J. Engström[1]

[1]Bedrock Construction and Site Assessment, Geological Survey of Finland, Espoo, Finland.
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Brittle structures of the bedrock fractures and faults play an important role in the suitability of bedrock volumes for different underground applications, let it be conventional underground construction where bedrock stability needs to be assessed or more advanced application, such as construction of deep geological nuclear waste repositories. In the latter case, faults and fractures form the main conduits for groundwater flow and form the main risk in respect to short- and long-term stability of the rock volume. In all of these underground applications, characterisation of brittle structures is therefore a crucial aspect. With the aid of both field-based and desktop-based studies, brittle structures can be mapped to a certain extent but due to time, resource and data constraints, it is typical that some areas and scales has to be overlooked during such studies. To address these shortcomings, a research project has been established at the Geological Survey of Finland to enhance the prediction of bedrock fracturing patterns in different scales and to enable better characterisation of fractures and faults of southern Finland.

The project, currently titled as "KARIKKO", will focus on four study areas in southern Finland: Vekara area, Åland Islands, Kopparnäs area and Hästholmen area. At each study area, the characteristics of fracturing and faulting will be studied at four different scales: 1) kilometre to 100 m scale (regional lineament interpretation based on geophysical and topographic material), 2) 100 to 1 meter scale (2D fracture maps based on UAV orthomosaics), 3) 1 meter to 1 centimetre scale (small-scale outcrop mapping) and 4) centimetre to sub millimetre scale (analysis of rock samples at the microscopic scale). The fracture datasets will include data on spatial location, geometry (orientation, length, form etc.) and topological parameters (intersections, connectivity, etc.). Further analysis of the collected fracture and fault datasets include the assessment of densities, orientation and length distributions at different scales and assessment whether these properties hold any scale invariance. If scale invariance can be shown to exist, this means that fracture properties can be predicted from observations from one scale. The role of pre-existing geological precursors, such as lithology and ductile structures, for the development of brittle structures in southern Finland will also be assessed during the project. If any correlation can be found, this can be utilised in the prediction of fracture characteristics in certain areas based on the existence of known geological precursors.

With the collected data sets, we aim to predict fracture properties from one scale to another through so-called prediction-outcome studies. Through the prediction-outcome analysis, we aim to validate the methodologies developed during the project. One main goal of the project is to develop methods for the collection of large datasets of fracturing and to automatize as many steps as possible in the workflow.

Lower-Carboniferous to Cenozoic deformation in the Irish Midlands, insights from integrated geological and geophysical modelling

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The recent adoption of 2D seismic reflection data as a mineral exploration tool has led to a substantial increase in the availability of 2D seismic data for the Irish onshore and the Carboniferous of the midlands, in particular. Combined with an extensive drilling archive, outcrop mapping and both airborne and ground based geophysical datasets, these geological resources provide an excellent basis for defining the 3D geometry of the Irish subsurface and for detailed mapping of Carboniferous to Cenozoic faults and associated growth sequences.

Kinematic analysis of faults has revealed a complex geological history, involving at least four phases of deformation. The geometry of lower Carboniferous normal faults arising from N-S crustal stretching is strongly influenced by the underlying NE-ENE trending structural grain of the Caledonian basement. Across-fault sequence thickness changes suggest that following the initiation of a large number of faults, activity was quickly localised onto a smaller number of major and longer lived faults, structures which ultimately accumulate displacements of up to ca 4km. Later Variscan compressional tectonics is not uniformly distributed, with inversion often localised on pre-existing normal faults. Permo-Triassic extension, often recognised offshore Ireland, is more difficult to identify from Carboniferous and older onshore sequences. Nevertheless, recent work has permitted the mapping of newly discovered Permo-Triassic normal faults and the lateral extension of associated previously identified faults. The final phase of faulting arises from Alpine-Pyrenean N-S compression involves the generation of NNW-trending dextral strike-slip faults, with displacements up to ca 7 km, and the sinistral strike-slip reactivation of pre-existing Lower Carboniferous and Permo-Triassic faults. These faults are mappable from the lateral displacement of Palaeocene dyke swarms imaged on newly acquired high resolution aeromagnetic data. Their presence is sometimes marked by geometrical effects associated with along-fault restraining or releasing bends and relays. Their localisation on pre-existing Carboniferous and Permo-Triassic normal faults, whose geometry is affected by even older Caledonian structure, highlights the importance of structural inheritance and the longevity of faults.

Fault-based PSHA, fault growth and interaction, and fault scaling relationships – the need for detailed primary data

Invited Keynote Speaker: Joanna Faure Walker[1]

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Changes in fault geometry, throw-rates and slip-rates along the length of a fault are crucial for understanding fault evolution and interaction and need to be incorporated in models of stress transfer, palaeoseismic investigation results, interpretation of fault scaling relationships and earthquake hazard assessments.

The geometry-dependent throw-rate model explains how changes in local fault strike and dip complicate along-fault throw-profiles. A series of real examples demonstrate the applicability of this model for both long-term throw-rates and the throw in individual earthquakes. This is important for understanding how measurements of offsets along a fault should be collected, interpreted and used; in particular, changes in throw as a result of changes in fault geometry have implications for interpreting palaeoseismic slip magnitudes and applying scaling law relationships to earthquake rupture parameters.

Fault-based PSHA (probabilistic seismic hazard assessment) can improve our ability to provide probabilistic hazard and risk assessments over those based solely on historical records by incorporating long-term rates from studies of active faults. However, currently such hazard assessments rarely incorporate variability in fault geometry and slip-rates, instead they rely on simplified planar structures with along-strike throw-rate or slip-rate profiles projected from one or a few measurements. Examples from the central Italian Apennines demonstrate how a lack of incorporation of detailed fault data alters PSHA. Firstly, excluding detailed along-fault throw-rate profiles alters calculated earthquake rates because calculated strain-rates and hence moment release rates are changed. Secondly, calculated ground shaking intensities at specific sites are altered due to changes in the source-to-site distance for ground motion prediction equations (GMPEs). Therefore, annual rates of exceeding specified ground shaking intensities at a specified site are changed. The examined faults demonstrate that the changes in implied recurrence intervals and expected shaking intensities can be beyond observed natural variability in earthquake recurrence rates and intrinsic uncertainties in GMPEs used for calculating shaking intensities. Therefore, detailed fault geometry and throw-rates and uncertainties in these when they are not known should be incorporated in the calculation of shaking intensities in calculations of earthquake hazard and risk.

How do we see fracture networks? The role of subjective bias in fracture data collection.

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Natural fracture networks often impart strong controls on the hydrogeological and mechanical properties of a subsurface rock mass. In order to understand a fracture network, several fracture attributes need to be classified (e.g. number and orientation of fracture sets, trace length distributions, aperture). Due to limitations of sub-surface data, surface analogues are often used to classify a fracture network, prior to using this data as inputs to sub-surface fluid flow, or ground stability models. The process of collecting fracture data requires the user to make a number of informed decisions (e.g. how a fracture terminates), which impacts fracture attributes (e.g. trace length). In other geoscience disciplines, particularly when users are required to make informed decisions (e.g. seismic interpretation; Bond et al., 2007), results are strongly effected by subjective bias. This study investigates the presence, magnitude and source of subjective bias on fracture data collected using A) linear scanlines and B) circular scanlines combined with network topology. The effect of time taken and participant experience is also investigated.

Variability in the number, trace length and abutting relationships of fractures were observed. Key factors impacting this variability included areas of limited exposure, fracture networks which contained several small fractures, whether an intersection is classified as a x-node or two y-nodes and the scale of observation used by the participant. The time taken and experience of the participant had no effect on fracture attributes. The relative percentage of small fractures and time taken by participants were consistant across all experiments undertaken individually. When data was collected as a group the time taken increased and fracture data collected tended towards the more detailed participant.

We suggest subjective bias in fracture data stems from personal character traits (e.g. broad brush vs detailed observations) and not from the level experience or geological training. Subjective bias significantly impacts fracture data collected as a group and limits the ability to compare or replicate studies. We also demonstrate circular scanlines, which require a minimum of 20-30 end points within the circle to be statistically valid, not only depends on fracture intensity, but also the user undertaking the scanline. Finally, the effect on Discrete Fracture Network (DFN) modelling is investigated and a number of recommendations are provided to improve the replicability and comparison of fracture data collected both in the field and using remote fracture mapping.

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Fluid circulation and fault-controlled diagenesis along a major syn-rift border fault system – the Dombjerg Fault and the Wollaston Forland Basin, NE Greenland

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During rift climax in marine rift basins, syn-rift border fault systems commonly displace hanging wall deep-water clastics against crystalline basement rocks. Such basement-juxtaposed successions represent challenging reservoir targets in hydrocarbon exploration, and it is therefore of great importance to understand the evolution of fluid flow properties as well as any fault-controlled diagenetic effects on the fault itself and/or adjacent basinal clastics. Border fault zones are also targeted for geothermal energy production (e.g. western Turkey), where fluid circulation and advective heat transfer is highly impacted by the fault properties and stark lithology contrast between clastics and crystalline basement.

Due to limited onshore exposure of such fault zones, studies on their evolution are rare and their impact on fluid circulation and in-fault, near-fault, and hanging wall sediment diagenesis is poorly understood. To tackle this circumstance, we here present the results of an ongoing investigation of a well-exposed example, namely the Dombjerg Fault in the Wollaston Forland Basin, NE Greenland.

Being part of the NE Greenland rift system, the Dombjerg Fault displaces Upper Jurassic and Lower Cretaceous syn-rift deep-water clastics against Caledonian metamorphic basement. We have previously shown that in addition to a significant ~1 km-wide damage zone, a ~700 m-wide envelope of increased cementation of the sediments developed around the fault core, termed chemical alteration zone. Now, based on further field, microstructural, clumped isotope, and fluid inclusion analyses we present a more detailed picture of the diagenesis of this zone and the fault core. Once formed, the chemical alteration zone had a significant impact on further mechanical deformation and fluid circulation. Fracturing and vein formation was promoted within the alteration zone, while deformation band formation occurred outside this zone. Subsequently, this lead to fracture fluid flow within and pore fluid flow outside the chemical alteration zone. Cement composition is predominantly calcite and dolomite, and veins exclusively consist of calcite, some of which show crack-seal texture. Initial formation of a microcrystalline vein calcite generation hosting wall-rock grains might be indicative for fluid overpressure in non-cemented areas prior to fracturing. Added to these structural and mineralogical observations, we will highlight the diagenetic differences in and outside the fault zone and present formation temperature of vein calcite and carbonate cement.

Our research on the Dombjerg Fault is the first comprehensive analysis of the in-fault and near-fault diagenesis associated with a syn-rift border fault zone, thus making it an excellent onshore analogue for rift settings worldwide.

How do variably striking normal faults reactivate during rifting? Insights from southern Malawi

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Active faults at the southern end of the Malawi Rift follow an arcuate bend in the regional amphibolite to granulite facies Proterozoic fabrics. Consequently, the rift's current stress state must allow for the reactivation of faults with a wide range of orientations. Fault kinematic indicators in the rift are, however, enigmatic and have been previously used to suggest either a NW-SE or SW-NE trending minimum compressive stress (σ_3). Here, this problem is addressed by calculating the stress ratio (σ_3/σ_1, where σ_1 is the maximum compressive stress) and effective coefficient of friction (μ_s') required for reactivation of the rift's variably oriented faults in different stress states. The stress states tested here are based on a previous collation of Malawi Rift earthquake focal mechanisms (Stress State 1: σ_3=06/242) and field observations of joint sets (Stress State 2 σ_3=00/082); the latter of which is also subparallel to the geodetically derived extension direction. Given that the dominant joint set in southern Malawi has a consistent N-S strike, we infer a uniform stress state and reject an alternative hypothesis that Proterozoic fabrics actively rotate stress along the rift. Though NW-striking faults are well oriented in Stress State 1, NNE-striking faults are misoriented (Fig. 1a). Their reactivation requires μ_s' ~0.5, which is inconsistent with the lack of frictionally weak phyllosilicates in the rift's faults. Stress State 2 is favoured since all faults are well oriented in it (Fig. 1b), and thus have μ_s' >0.6. In this context, faults in southern Malawi are slightly oblique, yet other studies find they exhibit near pure dip-slip. Previous analogue models demonstrate that this discrepancy can be reconciled if a deep-seated crustal-weakness is present. If true: (1) rift sections typically interpreted to be transfer systems between different basins can be extensional basins, (2) kinematic measurements are not necessarily an indicator of regional stresses, and (3) normal faults should not be excluded from seismic hazard analysis based on their apparent misorientation to other normal faults.

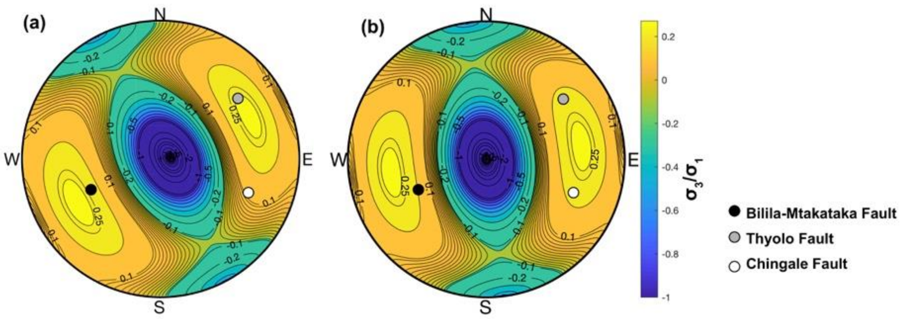

Figure 1: Stereplots contoured by the stress ratio, σ_3/σ_1, required to reactivate cohesionless faults in (a) Stress State 1 and (b) Stress State 2. The poles to three faults in the Malawi Rift are also shown and illustrate that all faults are well oriented for failure in Stress State 2, but NNE striking faults are misoriented in Stress State 1.

Structural inheritance in the Labrador Sea/Baffin Bay rift systems: Is the control by pre-existing crustal or mantle structures?

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Mesozoic-Cenozoic rifting between Greenland and Canada created the Labrador Sea and Baffin Bay, while leaving preserved continental lithosphere in the Davis Strait which lies between them. Inherited crustal structure has been hypothesized to account for the large-scale tectonic organisation of this region as it has in may other rifts and margins. In particular, the distribution of Paleoproterozoic accretionary belts has been related to the first-order segmentation in the subsequent rifted margin onshore field-based studies and offshore subsurface mapping. However, due to limited imaging of the region, the role of mantle lithosphere heterogeneities in continental suturing has not been fully explored. Our study uses three dimensional numerical models to analyze the role of crustal and sub-crustal heterogeneities in generating deformation. We implement continental extension in the presence of mantle lithosphere suture zones and deformed crustal structures and present a suite of models analyzing the role of local inherited structures related to the region. In particular, we investigate the respective roles of crust and mantle lithospheric scarring during an evolving stress regime in keeping with reconstructions of the Davis Strait. Numerical simulations, for the first time, can reproduce first order features that resemble the Labrador Sea, Davis Strait, Baffin Bay continental margins and ocean basins. The positioning of a mantle lithosphere suture, hypothesized to exist from ancient orogenic activity, produces a more appropriate tectonic evolution of the region than the previously proposed crustal inheritance. Indeed, the obliquity of the continental mantle suture with respect to extension direction is shown here to be important in the preservation of the Davis Strait. Mantle lithosphere heterogeneities are often overlooked as a generator of crustal-scale deformation. Here, we highlight the sub-crust as an avenue of exploration in the understanding of rift system evolution.

Simultaneous Extension and Contraction Facilitated by Strike-Slip Faults in the Phitsanulok Basin, Central Thailand

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The Phitsanulok Basin is a rift basin in central Thailand with over eight kilometers of Oligocene-Quaternary basin fill. The basin hosts a large oil field where hydrocarbons have been produced from fluvial-deltaic reservoirs in normal fault-related traps charged by lacustrine source rocks. The basin has a curved geometry in map view with the deeper northern half trending N-S and the shallower southern half trending NNW-SSE. It is bounded in the north by a NE-SW trending strike-slip fault (Uttaradit Fault); in the west by an east-dipping normal fault (West Boundary Fault); and in the south by a NW-SE trending strike-slip fault (Mae Ping Fault).

Opening of the basin started in the Middle Oligocene to Early Miocene (30-18 Ma) with the development of N-S and NNW-SSE trending normal faults. In the Middle Miocene (18-10 Ma) the basin experienced simultaneous extension in the northern part and contraction in the southern part. During the period, the West Boundary Fault continued moving as a normal fault with syn-kinematic deposition in its hangingwall whereas, in the south, existing basin fill and normal faults were respectively folded and inverted leading to notable uplift and erosion. After the Middle Miocene, the basin continued to evolve as a rift basin with thin post-rift deposition in the Pliocene to Recent.

The Middle Miocene anomalous deformation is attributed to stress rotation and reactivation of the strike-slip faults, the Uttaradit and Mae Ping Faults, respectively at the northern and southern margins of the basin. Both faults have been interpreted as pre-existing structures that were active under E-W compression in the Late Cretaceous-Paleocene. They probably had limited activities under NE-SW extension during the initial basin opening in the Oligocene to Early Miocene. In the Middle Miocene, N-S compression produced sinistral motion on the NE-SW Uttaradit Fault and dextral motion on the NW-SE Mae Ping Fault. Sinistral movement along the Uttaradit Fault facilitated normal faulting along the western boundary of the basin. At the same time, dextral motion along the Mae Ping Fault accommodated the eastward movement of the southwestern margin that led to contraction in the southern part of the basin. The model implies a counter-clockwise rotation of the whole western basin margin and that the Mae Ping Fault was reactivated in separate segments or patches.

Simultaneous extension and contraction provided the perfect setting for the petroleum system in the Phitsanulok Basin. The Middle Miocene subsidence and deposition in the northern part of the basin pushed the lacustrine source rocks into the oil-generation window, while inversion of the southern part of the basin created concurrent structural highs. The largest oil field in the basin, the Sirikit Field, is a structural high at the transition between those areas and in an excellent position to receive hydrocarbon charge from the source kitchen to the north.

A Greenland centered puzzle:
Updated plate reconstructions of the North Atlantic and Arctic

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Bridging spatial scales from faults, sedimentary basins, tectonic plates, to the entire lithosphere and mantle in order to understand the kinematic and paleogeographic evolution of a region demands a multifaceted, integrated approach. The evolution of the North Atlantic and Arctic domains have gained much attention in the last decade, partly courtesy of intensive mapping campaigns and conceptual and numerical modelling efforts. From a plate tectonic perspective, the post-Late Paleozoic history of the region has been largely dominated by rifting and seafloor-spreading but is notably interspersed by compressional and/or subduction events, as well as major extrusive and intrusive magmatic emplacements. Critically, Greenland lies at the centre of this region and its evolution is key piece for unlocking the kinematics of the surrounding regional puzzle.

To the east and west of Greenland, the North Atlantic has experienced an unusually protracted history of rifting, commencing after post-Silurian collapse of the Caledonides. Yet, the northern North Atlantic was one of the last pieces of the Pangea supercontinent to finally break apart, doing so at magnetic chron C24n in the east and debatebly ~C30-C27 in the west. A truly full-fit reconstruction for the region back to post-Caledonide collapse is still lacking (most models are limited to the last 200 Million years) and under and over-laps of Greenland's restored margins and/or extensive predicted compressional episodes are a ubiquitous feature of most existing models. Moving to the north of Greenland, the Eurekan Orogeny is a reconstruction challenge due to the heterogenous, distributed deformation and implications for proximal strike-slip motion. And further north, the kinematic evolution of the Arctic is somewhat more convoluted; the enigmatic timing and opening style of the Jurassic-Cretaceous Amerasia Basin owing largely to a disputed type of basement and magmatic overprinting. Yet, the scale of horizontal and vertical motion implied and knock-on implications for neighbouring domains demands a holistic approach.

Shifting from a traditional rigid plate tectonic reconstructions framework, the pre-breakup boundaries of the major plates (e.g. Greenland, Eurasia, North America and the Pacific) are here investigated through a dominantly non-rigid deformation framework. Using the *GPlates* software, we integrate new and legacy basin and plate-scale observations and models including conjugate seismic profiles and derived stretching factors, newly acquired geophysical mapping and paleomagnetism to generate a new set of digitally rotated markers, terranes and basins that are testable and refineable. Ultimately, this framework will deliver a new generation of paleogeographic maps and a discussion about processes such as rifting and breakup dynamics, sedimentary budgets and source areas, the role of along/within-margin heterogeneity structure, and the effect of time-dependent rifting rates.

Structural inheritance in multi-phase rifts: Examples from the northern North Sea rift

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Many continental rifts form through multiple phases of extension within highly heterogeneous lithosphere. Structural heterogeneities, including fabrics and shear zones in crystalline basement, and faults and lithospheric structure from prior rift events, may influence the nucleation and growth of normal faults, as well as the overall geometry and evolution of rifts. We use regional subsurface data to investigate how pre-existing structural heterogeneities influence the geometry, segmentation, and evolution of the northern North Sea rift throughout initial Permian-Triassic and later Late Jurassic-Early Cretaceous phases of extension.

Basement structure beneath the northern North Sea rift is largely related to the Caledonian orogeny and post-orogenic Devonian extension. Packages of intrabasement seismic reflectivity are identified beneath the rift and are interpreted as Caledonian and Devonian shear zones, which in some cases correlate to structures identified onshore. We find that these structures strongly influence the overall geometry of the North Sea rift during the Permian-Triassic rift phase, controlling fault geometry in some locations whilst inhibiting lateral fault propagation and segmenting the rift in others. Furthermore, these pre-existing basement structures, and structures associated with the Permian-Triassic rift, exert variable influence over the Late Jurassic-Early Cretaceous rift. In some areas, such as the Horda Platform, pre-existing structures are reactivated; whereas in other areas, such as the East Shetland Basin, pre-existing structures bear little influence over Late Jurassic-Early Cretaceous faults.

By summing fault heave accrued during each rift phase across key rift transects, we measure the strain across the rift during Permian-Triassic and Late Jurassic-Early Cretaceous rift phases. Strain is relatively uniformly distributed during Permian-Triassic rifting. However, during Late Jurassic-Early Cretaceous rifting, strains are higher in the north, across the East Shetland Basin and Horda Platform, than in the south, across the South Viking Graben and Stord Basin. Furthermore, Late Jurassic-Early Cretaceous extension contributes a larger, although still minor, contribution to cumulative North Sea extension in the north than in the south. We suggest that a stronger crustal terrane in the south, underlying the Utsira High, pins the eastern margin of the rift , effectively inhibiting the reactivation of structures further east and creating a narrow, localised rift focussed in the South Viking Graben.

The results of our study highlight the variable influence of structural inheritance in the evolution of multi-phase rifts and show how the influence of some structural heterogeneities may supercede that of others. This study highlights that models of rifting based on 'pristine' crust are unlikely to capture the complexity of natural systems.

Structural and geodynamic modelling of the influence of granite bodies during lithospheric extension: application to the Carboniferous basins of Northern England

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Intra-basinal highs within classic ‘block and basin’ style tectonic frameworks, in areas such as northern England, are underpinned by large granite bodies. This is widely believed to relate to the relative rigidity and buoyancy of granite in relation to accommodating basement. It has been suggested that during periods of tectonic extension, normal faulting around the peripheral regions of granite batholiths permits granite-cored blocks to resist subsidence, thus forming stable areas during periods of widespread faulting-induced subsidence. However, one-dimensional modelling indicates that relatively less dense crust is incapable of resisting subsidence in this way. Instead, when local isostasy is assumed, the occurrence of granite-cored, intra-basinal highs relates to initial isostatic compensation following granite emplacement. Differential sediment loading during extensional tectonism exaggerates this profile. An integrated two-dimensional lithospheric numerical modelling approach highlights the role of flexural rigidity in limiting the amplitude whilst increasing the wavelength of isostatic deflection. In light of these models, it is suggested that such a response leaves residual second-order stresses associated with the under-compensated buoyancy of the granite body and flexural tension.

The observed basin geometries of the Carboniferous North Pennine Basin can be replicated by incorporating a density deficiency within the crust, flexural rigidity, simple shear deformation within the shallower subsurface and pure shear deformation within the deeper subsurface. In adopting this technique, the regional flexural profile in response to underlying granite bodies and large extensional faults can be reproduced.

It is proposed that the interaction of three factors dictate the tectonic framework within a partially granitic, brittle-ductile lithosphere and the occurrence of inter-basinal highs: 1) non-tectonic, ‘second-order’ stresses such as the flexural response of the lithosphere and residual, under-compensated buoyancy forces in relation to granite bodies; 2) extensional tectonic stress and importantly; 3) inherited basement fabric.

On fault growth and bulk constriction in transtensional supradetachment basins

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In rift basins controlled by low-ß normal faults in the upper crust, accommodation is facilitated by combinations of faulting and extensionally forced folding. For basins that evolve adjacent to extensional faults of larger magnitudes, tectonic controls on sedimentation involve isostatic back-rotation of the extensional system and, commonly, the evolution and exhumation of large-scale extension-parallel folds and corrugations. These start to affect basin geometries when displacements accumulate beyond a certain magnitude and promote depocenter splitting and the formation of synclinal depocenters separated by an exhumed rift salient or core complex. In transtensional basins, strain partitioning leads to the development of folds and thrusts due to orthogonal contraction. Together, these structures facilitate complex patterns of accommodation that are likely to change over time. Based on field studies in the Devonian of western Norway, we document a basin evolution where large-magnitude fault growth and early inversion was followed by orthogonal shortening under bulk constriction. The first fault growth stage was characterized by footwall uplift and hangingwall basin formation, followed by more substantial and strongly differential footwall unroofing, moderate basin inversion and separation of the initial depocentre. Syndepositional constrictional deformation was characterized by coeval extension and orthogonal shortening and by a change in the maximum elongation trend. Renewed fault growth led to overstepping of the earlier synclinal depocentre, and to the burial of an earlier fold flank under a thick wedge of fault-controlled deposits. In transtensional basins, accommodation will be controlled by a complex interaction between extensional faulting, intrabasinal normal faulting and orthogonal folding and thrusting. Based on observations from `Old Red´ supradetachment basins in western Norway and the Pliocene basins surrounding the well-known `turtlebacks´ of Death Valley, we discuss the complex patterns of accommodation that may arise in so-called constrictional basins and the structural and stratigraphic architectures that may result.

Controls on the late Neogene transition from marine to terrestrial deposition in the Central Myanmar Basin

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The Central Myanmar Basin is a Cenozoic basin developed between the Sunda block in the east and an accretionary wedge in the west, above the subducting Indian plate. Benthic foraminifera and other associated evidence suggests that sediments that comprise the basin's Miocene strata were derived from the north and deposited in a shallow-marine to estuarine environment. A pronounced shift to terrestrial sedimentation, however, occurred in the late Neogene (approximately 16 – 11 Ma) along with the southward progradation of the Ayeyarwaddy delta. There is robust evidence for this change, but the cause remains contentious. We present a geophysical interpretation from the basin and tectonic and non-tectonic hypotheses for the late Neogene transition.

Reflection seismic data suggest that, prior to the Neogene transition, the boundary between the present-day Salin and Pyay sub-basins was dominated by a swarm of ENE-WSW normal faults, while other parts of the Central Myanmar Basin were relatively more stable. The termination of these extensional faults is marked by a surface that, in many places, is expressed as an angular unconformity or onlap truncation associated with the change in tectonic regime. However, in places the truncation is not clearly associated with evidence for tectonic inversion and uplift. Where there is evidence for subsequent uplift, it occurred in different places at different times, beginning with uplift of the Bago Yoma hills in the east of the basin while estuarine conditions were still present in the center of the basin. Uplift then occurred more widely, deformed the earliest instances of the unconformity and transformed the basin to a fully terrestial condition.

Structural and sedimentary diachroneity may indicate a tectonic control on the depositional environment. However, this interpretation is not consistent with all the observations, and processes such as dynamic topography and/or eustatic sea level changes may also be involved in different parts of the basin at different times. Processes driving the Neogene change may include regional-scale factors such as the northward motion of India outboard of Myanmar, the gravity-driven flow from the Eastern Himilayan Syntaxis, subduction below western Myanmar, flexure related to accretion in the west, and onset of the Sagaing fault, a strike-slip partition of the oblique margin.

Deformation mechanisms, structural diagenesis, and petrophysical properties of calcite- and dolomite-rich fault rocks

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Deciphering the role played by cataclasis of carbonate fault rocks on both amount and distribution of connected porosity is of paramount importance to assess the fault permeability. Despite the great importance of this knowledge, the detailed evolution of the pore network in carbonate fault rocks is still matter of debate due to a paucity of published experimental data. Moreover, the contribution of structural diagenesis on their time-dependent evolution is quite unknown. The present work focuses on extensional fault zones in platform carbonates, which crop out along the axial sector of the central and southern Apennines, Italy, and were exhumed from depths <1.5 km during Plio-Quaternary downfaulting. In the field, we first documented the inner fault core architecture of both limestone- or dolostone-hosted fault zones, which is made up of both grain- and matrix-supported fault rocks. The former ones mainly localize within the outer fault core domains that flank the fractured and fragmented carbonates of the fault damage zones. Differently, matrix-supported fault rocks localize in the innermost domain of the fault cores adjacent to the main slip surfaces. There, very highly comminuted fault rocks often cemented are also present.

In the laboratory, about 50 selected hand specimens were analysed by mean of X-Ray diffraction, optical microscopy, SEM-Cathodoluminescence, digital image analyses, porosity and permeability measurements, and ultrasonic test at cycles of increasing confining pressure. As a result, we deciphered the main micro-mechanisms associated to cataclasis, and assessed those responsible to physical and chemical compaction, as well as to cementation during the fault rock diagenetic evolution. The grain-supported fault rocks formed primarily due to Intragranular Extensional Fracturing, whereas chipping was predominant in the matrix-supported ones. Concurrent physical, chipping and shear fracturing, and chemical, thermal decomposition of carbonates, developed within the highly comminuted cataclasites. Results are hence consistent with both calcite- and dolomite-rich fault rocks affected by similar cataclastic micro-mechanisms, but quite different diagenetic processes. In fact, during fault evolution and exhumation, chemical compaction by mean of grain interpenetrations and pressure solution and multiple generations of calcite cement occurred primarily only within the limestone-hosted fault zones.

We discuss the petrophysical and ultrasonic data in terms of the possible control exerted by both cataclasis and diagenesis on the measured values of porosity, permeability and P-wave velocities. In fact, we document that the specific pore networks of dolomite- and calcite-rich fault rocks are linked to the hydraulic behaviour of carbonate-hosted fault cores. Specifically, dolomite-rich fault rocks include crack-like, soft pore networks due to latest exhumation stages and paucity of calcite cementation, which are characterized by a quite isotropic, homogeneous permeability. Differently, dichotomic pore networks characterize calcite-rich fault rocks. An elongated, soft pore network is present within the grain-supported fault rocks, whereas mold-like, stiff pores are documented in the matrix-supported fault rocks. Such a structural configuration is also profoundly affected by localized calcite precipitation within the most comminuted fault rocks adjacent the main slip surfaces, determining a strongly reduced cross-fault permeability in the limestone-hosted fault cores.

Structural controls of fault-zone fluid flow, and hydraulic connectivity between active border faults and rift basins: constraints from the Bwamba Fault, East African rift.

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Understanding the architecture and permeability of crystalline basement fault zones and their relationships with associative sedimentary cover rocks has become increasingly important in hydrocarbon exploration and production [1], geothermal energy [2] and may have implications for carbon capture and storage [3]. Here, we present a detailed description of the Bwamba Fault, a well-exposed rift border fault hosted by an Archaean gneissic-basement complex, and sedimentary rocks of the Semliki Basin in the western East African Rift System (EARS), Uganda. Our aim is to establish the spatial controls of fault zone fluid flow, and the potential for hydraulic connection between basement fault and basin sedimentary rocks.

The Bwamba Fault core is composed of discrete cataclasite-series units with varying fluid-rock interaction textures and structural fabrics that indicate dominant extensional kinematics, and minor fault-orthogonal strike-slip components associated with minor transverse strike-slip faults. These fabrics are preferentially mineralised, indicating they were favourable fluid pathways. Two major phases of fluid ingress occurred in the fault zone; the first caused localised quartz, feldspar and carbonate veining and likely involved basement fluids, whilst the second is represented by a major influx of Fe- and S-bearing fluids that facilitated wide-spread jarosite and Fe-oxide mineralisation, particularly in high-permeability protocataclasites. We suggest that a major hydrogeological shift occurred between the first ingress event, where the Bwamba Fault juxtaposed basement with basement, and the second, where it came into contact with fluids carrying dissolved ions derived from Fe and gypsum-rich mudstones of the Semliki Basin during progressive deformation. Such evolving permeability connections between basement faults and hanging-wall sedimentary rocks have local importance for hydrocarbon systems in the Albert Rift and geothermal energy resources of the Semliki Basin [2], and may be commonplace in active rifts [5].

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Fault Void Fills: Reactivation, frictional melting, and void formation during ancient earthquakes

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Natural fault systems are typically complex, with networks of potentially inter-linked cavities filled with a variety of geological materials. These "fault void fills" are widely recognised in both subsurface cores, and surface exposures; and are thought to exert a significant control on the potential for fluid migration pathways in the brittle upper crust. The geological characterisitics of these fills, such as fill-type, longevity, or connectivity, are likely to vary with depth, so by understanding the formation and filling processes at different paleaeodepths we can begin to make predictions about the hydrodynamic properties of upper crustal fault zones, both in the present day and back through geological time. Here we examine examples of fault void formation and filling from the Lewisian Complex of the NW Highlands which formed at the base of the seismogenic zone, between 10-15km. Contemporaneous interlinked systems of foliation parallel faults and cross-cutting 'ladder fractures' and fills are well exposed in part of the Canisp Shear Zone (CSZ) at Achmelvich. These so-called 'Late-Laxfordian' brittle structures post-date ductile Proterozoic deformation, responsible for the formation of the NW-SE sub-vertical shear zone (Inverian, Laxfordian, ca. 1.75-2.4 Ga) and pre-date deposition of the overlying Stoer Group ca 1.2Ga. In the CSZ, NW-SE trending sinistral faults reactivate the ductile shear zone fabric, while the contemporaneous N-S dextral-normal ladder fractures cross cut the foliation at high angles and are widely associated with dilatant zones of brecciation and mineralization (the fault voids). Friction melts (pseudotachylites) are generated along the foliation-parallel fractures and locally injected into ladder fracture void spaces. The insights gained at Achmelvich identified new mechanisms for tectonic void formation and filling, showing that even at depths close to 15km, fault networks can preserve cm scale cavities, enabling and actively driving fluid migration through the upper crust.

A multidisciplinary approach to unravel fluid circulation and tectonic evolution within shallow crustal potentially seismogenic fault zones

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Understanding the tectonic evolution and paleo-fluid circulation within surface-exposed fault zones is fundamental to predict the present-day seismic-behavior and the barrier/conduit attitude of faults imaged at depth by seismic reflection profiles and by other indirect techniques. To do so, it is necessary to answer the three “Ws” and “H” geological questions concenring the time (When?), depth (Where?), type of circulating fluids (Who?), and deformation mechanisms (How?) involved during faulting. For this reason, a multidisciplinary approach, combining structural geology and geochemistry, is essential for the comprehensive reconstruction of such geo-history. We present two case studies of surface-exposed fault zones from the central Apennines: (1) the Val Roveto fault, an exhumed seismogenic fault active since early Pliocene time and (2) the broken formation of the Mt. Massico ridge, an exhumed analogue for potentially-seismogenic intra-wedge tectonic mélange. In the first case study, stable O, C, and Sr isotopes, clumped O isotopes, whole rock geochemistry, fluid inclusion analyses, and U-Th dating combined with strucutral analyses and geological mapping showed that comb- and slip-parallel veins precipitated in Late Pleistocene (between 121 ± 1 Ky and 317 ± 49 Ky) at a maximum depth of ~350 m time below the present-day outcrop level at temperatures between 32 and 64 °C. The observed warm temperatures are not compatible with a shallow (< 500 m) precipitation depth, which, in this region, is dominated by circulation of cold meteoric-derived waters. Therefore, deep-seated and crust/mantle-derived warm fluids were squeezed upward during earthquakes and were responsible for calcite precipitation at shallow depths in co-seismic comb- and slip-parallel fractures. In the second case study (still ongoing study), structural analyses, paleothermal indicators (illite/smectite mixed layers), and U-Pb geochronology on syn-tectonic calcite-filled mineralizations allowed to constrains the deformation dpeth and the timing of syn-orogenic compressional (between 7.0 ± 1.6 and 5.1 ± 3.7 My) and post-orogenic (2.85 ± 0.5 My) extensional phases that affected the Mt. Massico broken formation.

Variation in style of magmatism and emplacement mechanism induced by changes in basin environments and stress fields (Pannonian Basin, Central Europe)

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The development of high-resolution 3D seismic cubes has permitted recognition of variable subvolcanic features mostly located in passive continental margins. Our study area is situated in a different tectonic setting, in the extensional Pannonian Basin system (central Europe) where the lithospheric extension was associated with a wide variety of magmatic suites during the Miocene. Our primary objective is to map the buried magmatic bodies, to better understand the temporal and spatial variation in the style of magmatism and emplacement mechanism within the first order Mid-Hungarian Fault Zone (MHFZ) along which substantial Miocene displacement took place. The combination of seismic, borehole and log data interpretation enabled us to delineate various previously unknown subvolcanic-volcanic features. In addition, a new approach of neural network analysis on log data was applied to detect and quantitatively characterise hydrothermal mounds that are hard to interpret solely from seismic data.

The volcanic activity started in the Middle Miocene and induced the development of extrusive volcanic mounds south of the NE-SW trending, continuous strike-slip fault zone (Hajdú Fault Zone). In the earliest Late Miocene (11.6-9.78 Ma), the style of magmatic activity changed resulting in emplacement of intrusions and development of hydrothermal mounds. Sill emplacement occurred from south-east to north-west based on primary flow-emplacement structures. The time of sill emplacement and the development of hydrothermal mounds can be bracketed by onlapped forced folds and mounds. This time coincided with the acceleration of sedimentation producing poorly consolidated, water-saturated sediments preventing magma from flowing to the paleosurface. The change in extensional direction resulted in change in fault pattern, thus the formerly continuous basin-bounding strike-slip fault became segmented which could facilitate the magma flow toward the basin centre.

Transient thermal effects in sedimentary basins with normal faults and magmatic sill intrusions – A sensitivity study

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Magmatic intrusions are known to greatly affect the basin temperature in their vicinity. However, faulting and physical properties of the basin may influence the thermal magnitudes of the intrusions and furthermore the potential source rock maturation. Sills may intrude during structural events and erases the traces of pre-intrusion hostrock temperatures. Two transient thermal effects thus operate simultaneously in the basin. Here we present results from a sensitivity study of the most important factors affecting the thermal history in structurally complex sedimentary basins with magmatic sill intrusions. These factors include effects related to faulting, physical properties and restoration methods; 1) fault displacement, 2) time span of faulting and deposition, 3) fault angle, 4) thermal conductivity and specific heat capacity, 5) basal heat flow and 6) restoration method. All modeling is performed on the same constructed clastic sedimentary profile containing one normal listric fault and with one faulting event. Sills are modeled to intrude into either side of the fault zone of the same profile with a temperature of 1000 ºC. The results show that transient thermal effects may last up to several million years after fault slip. The amount of fault displacement, time span of faulting and deposition, thermal conductivity and basal heat flow are the factors that have the most significant influence on pre-intrusion temperatures in the basin, and keep the basin thermally unstable for the longest period of time. Sills emplaced with a delay in relation to fault slip, intrude into a warmer environment, and has greater impact on the potential source rocks maturation levels. Thermal differences up to 40 ºC could occur for sills intruding at time of fault slip, to sills intruding 10 million years (Myr) after fault slip. We have shown that the transient thermal effects of structural development in basins with magmatic intrusions play an important role, and omitting these effects may lead to over- or under-estimation of the thermal effects of intrusions and ultimately the estimated maturation levels.

Igneous intrusion segments as a record of intrusive sheet growth and emplacement mechanisms?

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For many decades it has been recognised that most upper-crustal igneous sheet intrusions consist of stepping, sub-parallel segments. This is noted from field observations of preserved non-linked segments, as well as abandoned tips (or 'horns'; akin to segmented mineral vein sets) located along the margins of through-going sheet intrusions. Intrusive segments, lobes, and fingers are typically inferred to represent the early stages of propagation and formation of a through-going sheet intrusion (e.g., a dyke, sill, or cone sheet). In reality, those segments actually represent the very final stage of intrusion arrest, and therefore, the magma that wasn't moving. Although most early models involved elastic-brittle emplacement – the development of extension fractures – numerous more recent studies have highlighted alternative emplacement mechanisms, such as viscous emplacement, indentation, or host rock fluidisation. Segment morphology is largely related to host rock behaviour and deformation mechanisms during emplacement. This can have important implications for how magma transits the crust, and informs models for intrusion propagation, geometry, and distribution in the subsurface.

The intrusive segments that are used as base observations for emplacement models typically occur at the periphery of intrusive sheets; hence they are a record of the very final stage of emplacement, rather than the 1st increment of sheet growth. Here we present examples of segmented sills from the Isle of Skye, Scotland, and San Rafael Desert, Utah (USA), that highlight the variable nature of intrusions between early- and late-stage segments. In both cases, the sills intruded thinly-bedded sand-silt-mudstone sequences. Early-stage segments can be recognised at positions along through-going sill sheets, based on preserved tip zones (horns). Horn geometry, appearing as tapered tip zones, and host rock deformation textures, indicate dominant elastic-brittle emplacement. In contrast, sill segments at the periphery of sheets exhibit lobate to blunt-ended geometries; host rock deformation textures indicate viscous indentation and/or fluidization. We suggest that this transition from brittle to non-brittle emplacement reflects the changing conditions of both the magma and host rock during emplacement. During the early stages of emplacement, magmas entering the system may be hotter, have few crystals (and/or bubbles), and may have have higher volatile content; all generally contributing to low viscosity. In contrast, segments at the periphery of the intrusion – beyond which the sill did not propagate – are likely to be more viscous due to cooling, crystal growth, and volatile exsolution/loss. Such effects can contribute to order-of-magnitude scale viscosity increases in magmas, potentially pushing the system towards viscous emplacement processes. Since emplacement models are generally tuned to field observations, it is therefore important to account for the temporal changes to magma and host rock properties that are inherent in the growth of sheet intrusions.

Tectonic controls on Taupo Volcanic Zone geothermal expression

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The Taupo Volcanic Zone (TVZ), a bark-arc rift, hosts the majoirty of New Zealand's geothermal reservoirs. The structural architecture of the plumping of these geothermal systems is important to characterise and understand as it controls geothermal fluid circulation at a local scale (within individual reservoirs) and at the regional scale (geothermal expression across the rift). Information on the structure, stress, and their inter-relationship in a geothermal field is essential for understanding structurally controlled permeability, and when related to larger scale structural mapping can help us refine fault, fracture and fluid flow architecture. We present here new data from active fault mapping, borehole image logging, and well testing in the Te Mihi production area of the Wairakei Geothermal Field, New Zealand.

Data shows the Te Mihi area to be structurally complex, with a set of active NW dipping master faults, with pervasive SE dipping antithetic and splay structures in their hangingwalls, intersected by a second active master fault set striking E-W, dipping south. Further subordinate, spatially localized, N-S striking structural trends are also identified. In consideration with GNSS vectors both active NE-SW, and E-W fault trends are thought to creat biaxial extension in this region of the TVZ. However, the dominant NE-SW S_{Hmax} orientation found within boreholes suggests that NW-SE extension dominates the regional stress, or that N-S directed extension is temporal.

Fluid flow within boreholes is supported by NW dipping master faults, travel time fractures on acoustic image logs, halo fractures on resistivity image logs, NE-SW and E-W striking fractures, intervals of high fracture density, and spatial concentrations of wide aperture fractures and recently active NE-SW and E-W striking fractures.

This study suggests that the Te Mihi geothermal expression is a result of this area undergoing biaxial extension, evident from active structural trend intersections in the area, and the predominance of NE-SW and E-W striking structures within permeable zones. Biaxial extension is therefore an important control on crustal fluid flow within the Taupo Volcanic Zone and thus geothermal resource delineation.

How do normal faults grow above dykes?

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Dyke intrusions feed volcanic eruptions and drive crustal extension. Yet many dykes stall and thicken at depth, inducing formation of normal fault-bound graben in the overlying rock. Monitoring seismicity and ground deformation generated by these dyke-induced normal faults is used to track active dyke intrusion and estimate dyke properties (e.g. volume), which are critical to volcanic hazard assessment. Similarly, dyke-induced normal faults control the geomorphology of volcanic rift zones, providing accessible surficial records of how magmatism shapes continental break-up, seafloor spreading, and other planetary bodies. Whilst understanding how dyke-induced normal faults grow above dykes is thus fundamental to a wide-range of volcanic, tectonic, and surface processes, their geometrical and kinematic relationship remains unclear because we cannot view natural examples in 3D. Here we use seismic reflection data to map the 3D structure of graben-bounding, dyke-induced normal fault arrays developed above a a dyke swarm offshore NW Australia. The dykes can be mapped over numerous 2D and 3D seismic surveys and extend for >200 km along-strike; dyke-induced normal faults are commonly observed above individual dykes and can be traced for >100 km along-strike. By mapping multiple areas of high displacement (up to ~150 m) across the dyke-induced normal faults, we show nucleation occurred at various heights between, but not at, the dyke tip or contemporaneous free surface. Faults grew via linkage of discrete slip surfaces, likely in response to the incremental injection of a laterally propagating dyke. Our results highlight the surface expression of dyke-induced normal faults is controlled by where they nucleate, meaning fault properties at the surface cannot be easily related to underlying dyke properties. However, analysis of fault kinematics can be used to reconstruct dyke emplacement mechanics and flow direction. Furthermore, we show that the dyke-induced normal faults are much longer and have lower displacements than tectonic faults; i.e. on maximum displacement-length plots they occur outside the range of tectonic faults. Seismic reflection data can thus be used to distinguish dyke-induced normal faults from tectonic faults, therbey providing a method for mapping dyke swarms on other continental margins.

Stress state versus host-rock lithology as a control on architecture of igneous sheet intrusions

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Intrusive complexes comprise linked networks of sills, dykes, and inclined sheets, and these commonly have complex architectures. The role of lithological heterogeneity and stress state in controlling this architecture is currently a topic of debate. Dyke emplacement is commonly associated with tectonic extension, whereas sill emplacement is usually attributed to a low-deviatoric stress state, where pre-existing discontinuities can promote local σ_3 rotations. Some recent studies, however, suggest that sill-dyke networks may represent a single tectonic stress state, where existing strucutres and/or lithological layering cause only local deviations in the overall intrusion geometry. Other recent studies and datasets show that lithological heterogeneity have a dominant control on intrusive architecture. In this contribution, we take a combined approach to investigate the influence of both the tectonic stress state during emplacement, and host rock lithology, in a spectacularly exposed example of a Paleogene sill complex in East Greenland. The ~10 m thick dolerite sills were emplaced into sandstone and shales, and the outcrop has been imaged in a 32x0.3 km virtual outcrop model, constrained by lithological logs. The intrusions are also imaged by 2D seismic data.

Dykes in the study area strike E-W and ESE-WNW, and several dykes show continuity with sill segments, suggesting contemporary emplacement; host rock bedding highlights shear offsets across dykes in those cases. Sill segments mainly follow planar bedding of the host-rock, and the amount of igneous material in the sills is ~100 times higher than in the observed dykes. The outcrop data show clear host-rock control on sill architecture at the scale of a meter to a few hundreds of meters, where sills follow mudstone beds. However, sills also locally step upwards towards the north, transgressing the layered host rocks at ~7° over a lateral scale of several kilometres. In mudstone-rich sections, sill segments are short (200 m) and have vertical separation distances on the 20 m scale. In sections with thick, homogneous sandstones interbedded with regionally extensive mudstones, sill segments are relatively long (several km), with larger vertical separation distances (150 m). In the reflection seismic dataset, which has much lower resoltuion, sills cross-cut stratigraphy at all levels in the basin (including basement, pre-rift, and post-rift sedimentary rocks), with a consistent northward ascent at ~7°.

Our mechanical models based on dyke and sill contact attitude data, combined with field observations of feeding relationships, indicate that σ_3 was near-vertical for both dykes and sills; σ_1 was oriented horizontal and E-W, with σ_2 horizontal and N-S. We calculated a stress ratio of 0.25, consistent with a near-radial extension in the vertical plane. We infer that sill segment geometry, and the transition from dykes to sills (or vice versa) is controlled by the contrast in properties of the host rock lithology. In cases where host rocks are homogenous, initial fractures – and therfore sills – are more distributed and shorter than sections that exhibit a strong mechanical contrast. The overall trajectory of the intrusive suite, however, is controlled by the regional stress state. This study has potentially major implications for predicting the location and distribution of sill complexes in layered sedimentary units.

The Structure and Responses of Carbonate Sediments To Salt Tectonics: New Insights from 3D Seismic and Outcrop Analogues

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Salt tectonics on passive margins mainly reflect oceanward flow of the salt triggering intense and fast deformations of the overburden. Strong along-strike variations in the style and timing of the salt structures make difficult to assess the kinematics of such a 3D complex structural pattern. This is key to adress sedimentary systems in such settings and, therefore, the distribution of potential reservoirs and source rock.

In the NW Gulf of Mexico, salt tectonics in the uppermost part of the passive margins display extensional raft tectonics of fragmented pre-halokinetic Middle Jurassic Norphlet sandstone and Base-Smackover carbonates. An exceptional high quality 3D seismic survey revealed spectacular megastriations at the top of the Louann salt layer reflecting irregular displacement vectors of the salt flow. Changes in the rafts trajectory appear to reflect translation over uneven basement topography. Structural segmentation of the raft pattern coincides with 1st-order megastriations while a 2nd-order megastriations are the imprint of the dead faults translated and rotated down by salt spreading.

We coupled those kinematic markers with 2D structural restorations to reconstruct in map the trajectories of the individual rafts through time. Strong strike- and dip-variabilities show that the rafts are strongly diachroneous and display increasing segmentation and internal deformation together with the cummulated displacement.

Distribution of the syn-raft carbonates is strongly affected in time and space. The Mid-Jurassic carbonate system is divided into stable and rafted domains. In the stable domain, accommodation is limited and a large scale ramp shows a 420 m aggradation of progradation-dominated system perpendicular to rafting. In the rafted domains, high accommodation rates result in progradational-aggradational-backstepping geometries in roll-overs hangingwall. Onshore outcrops display similar observations such as in the Southern Pyrenees, in Angola or Morocco where carbonate systems are very sensitive to the rapid changes of paleo-bathymetry induced by salt related deformation.

Intrasalt Structure And Strain Partitioning In Layered Evaporites: Insights From The Messinian Salt In The Eastern Mediterranean

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The Messinian Salinity Crisis is a remarkable geological event which resulted in the widespread deposition of a thick, layered evaporite unit across the Mediterranean Basin, subsequently buried by a thick clastic overburden. The Messinian evaporitic sequence is lithologically heterogeneous. The halite-dominated units are interbedded with other salts, in addition to clastics or carbonates. This lithological heterogeneity can lead to rheological heterogeneity, with the different mechanical properties of the various rock types controlling strain partitioning within deforming evaporites.

Determining the composition and internal structure of salt bodies is important for safe drilling through thick salt sequences, and enables us to build better velocity models that allow more accurate seismic imaging of subsalt geology. However, due to typically poor seismic imaging, and a lack of outcrop and well data, the nature of this lithological control on intrasalt deformation is still poorly understood.

The heterogeneous Messinian evaporites are highly reflective, shallowly buried and only weakly deformed along the Levant Margin in the eastern Mediterranean. This means that they are well imaged by seismic data and provides us with a unique opportunity to assess how: (i) intrasalt strain varies within thick salt during the early phase of margin development; and (ii) in the context of the Eastern Mediterranean, how the intrasalt seismic-stratigraphic architecture links to the geodynamic context and evolution of this tectonically complex region.

We use high-quality 2D and 3D seismic reflection data covering a large area offshore Lebanon to map intrasalt structural style. The strong, competent layers embedded within the ductile halite units are highly reflective and deform in a brittle manner, recording intrasalt strain. This enables us to calculate strain on individual intrasalt reflectors to show horizontal and vertical variations across the study area. From this we can determine how lithological and thus mechanical heterogeneity affects the structural evolution of the salt during early stage salt tectonics.

Structural Style of Early Stage Salt Tectonics: insights from 3D Seismic Data, offshore Angola

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Salt-bearing passive margins are characterized by kinematically linked domains of updip extensional and downdip contractional, thin-skinned (i.e. suprasalt) deformation, separated by a domain of translational. Deformation is driven by gravity instabilities related to basinward tilting (i.e. gliding) or differential loading (i.e. spreading) of the salt detachment. The way in which salt and its overburden deform in response to gliding and spreading is complex, especially in the presence of significant base-salt relief and spatially variable patterns of suprasalt sedimentary loading. This variability creates uncertainty when attempting to unravel the regional kinematic history of salt-bearing passive margins, particularly during the early-stage of deformation when gravity is a key driving mechanism.
This study uses a high-quality, depth-migrated three-dimensional seismic dataset located on the slope between domains of updip extensional and downdip contractional, offshore Angola. We use seismic-stratigraphic and seismic attribute analysis of Aptian salt and its immediate Albian overburden to document structural styles during the early-stage development of a salt-bearing passive margin.

Our data reveal a range of salt structures and salt-related faults. In the updip extensional domain, we document N-S and NW-SE-striking normal faults that have salt rollers developed in their footwalls; these faults and salt structures formed in response to tilting of the salt and overburden stretching, related to opening of the South Atlantic. Kinematically linked downdip contractional domain is accommodated by a series of N-to-NW-trending salt-cored Albian anticlines and squeezed diapirs, in addition to NW-SE-striking thrust faults. Between the updip and downdip domains, several N-to-NE-trending salt walls and NE-SW-striking strike-slip faults are documented. The NE-SW-striking strike-slip faults form single, continuous, through-going structures, or are strongly segmented and composed of numerous shorter structures, with both style of fault best-developed at the edges of allochthonous salt bodies. The strike-slip faults strike perpendicular to the regional extension direction, thus we suggest they form to accommodate along-margin variations in the magnitude and direction of downslope overburden translation.

We show that careful analysis of supra-salt fault networks and underlying salt structures can provide important insights into the early stage kinematic development of salt-bearing passive margins, such as those characterising the South Atlantic margin.

The importance of basement configuration on the development of salt structures in confined salt-related basins: insights from analogue modelling

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The presence of salt layers is a common observation in many rift basins of the Norwegian continental shelf (e.g. Norwegian Danish Basin, Nordkapp Basin) and in other rift basins in the world. During rifting, these deposits precipitate in a series of grabens and half grabens delimited by synthetic and antithetic faults which commonly display along-strike changes in orientation as well as throw. Previous studies indicate that the post-depositional mobilization of these evaporitic layers result in the formation of salt structures and minibasins whose distribution are strongly influenced by the occurrence of sub-salt faults. In this study, we use analogue scale models with different basin configurations to investigate the impact of sub-salt faults on the dynamics of differential loading in confined salt-related basins, with emphasis on the timming and distribution of salt structures. In the first model, we reproduce the progradational loading of salt deposited in a graben limited by a proximal fault dipping 60° in the progradation direction, and a distal fault dipping 60° in the opposite direction. The distal fault is parallel to the proximal fault for about ½ of its length, but then it changes in strike such that the graben narrows along strike. This model results in the formation of expulsion rollovers that progressively migrate forming salt welds as salt is evacuated in the progradation direction. Differential loading of salt near the proximal fault causes the formation of thin-skinned faults in the overburden which could be misinterpreted as thick-skinned faults through the entire succesion. On the other hand, the distal fault favours the inflation of pillows and formation of salt diapirs, whose distribution coincides with changes in fault strike. In the second model, we additionally introduce in the graben an intrabasinal fault dipping 60° opposite to the progradation direction. This intrabasinal fault strongly affects the timming of salt mobilization, resulting in the earlier generation of salt diapirs and formation of salt welds with respect to the first model. In these two models, the sub-salt faults are inactive and the graben geometry is fixed. A third ongoing model, analyses the impact of introducing extension and active thick-skinned faulting. We use the results of these experiments to explain the differences in timing and distribution of salt structures along confined-salt related basins such as the Nordkapp Basin in the Norwegian Barents Sea.

Growth and inversion of a salt-rich oblique rifted margin, eastern North Pyrenees

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We present a field-based tectonic and stratigraphic study of key areas along the inverted proximal margin of the salt-rich Aptian-Albian rift system (rift margin to necking domain), preserved in the eastern Pyrenean retroforeland, and the North Pyrenean Zone, southern France. We reconstruct the migration of extension, subsidence and uplift across the rift margin and necking zone during Aptian-Cenomanian rifting and the distribution, style and intensity of deformation during Pyrenean inversion. These structures provide excellent field analogues for presently buried salt-related structures of passive margins. Halokinetic sequences are used to reconstruct the Aptian-Albian infill of several transtensive salt-based basins and to identify salt related structures such as salt welds and diapirs. The presence of rafts, olistoliths, gypsum breccias and bipyramidal quartz in Albian marine strata records erosion of adjacent active diapirs. Apto-Albian depocentres increase in scale and facies deepen to the south (up to 3 km of deep marine marls and turbidites) indicating deepening of the detachment level. Pyrenean folding of principal depocentres increases in intensity southward, coupled with inversion of major faults. Triassic salt acted as a decoupling level between deforming cover and thickening basement below. Anticlines and thrusts focus on salt walls and are frequently replaced by salt welds between two depocentres. The east-west trending North Pyrenean Frontal Thrust itself comprises a series of inverted normal faults associated with salt walls that defined the northern edge of the necking zone.
On the scale of the whole orogen, we compare and discuss the role of salt in the evolution of the European margin (northern Pyrenees) with that observed on the Iberian margin of the Apto-Albian rift system (southern Pyrenees) and their subsequent inversion.

Untangling subduction interface and upper plate fault coastal deformation signatures to constrain the seismic hazard of the Hikurangi subduction margin, New Zealand.

Invited Keynote Speaker: Kate Clark[1], J. Howarth[2], N. Litchfield[1], U. Cochran[1].

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The Hikurangi subduction margin, New Zealand, has not produced large subduction earthquakes within the short written historic period (~180 years) and the potential of the plate interface to host large to great earthquakes and tsunamis is poorly constrained. The geological record of past subduction earthquakes offers a method for assessing the magnitude and frequency of subduction earthquakes to underpin seismic and tsunami hazard assessments. However, the Hikurangi margin is characterised by ubiquitous active upper plate faults and the isolation of evidence specifically relating to past subduction earthquakes is challenging. Large historic upper plate fault earthquakes such as the AD 1855 M 8.2 Wairarapa, 1931 M 7.8 Hawke's Bay and 2016 M_W 7.8 Kaikōura earthquakes demonstrate that upper plate fault earthquakes can cause coastal deformation and tsunamis, similar to the effects expected for a subduction earthquake. Using a compilation of coastal coseismic deformation and paleotsunamis from 22 locations along the Hikurangi margin, we use along-margin temporal correlations to identify 10 past possible subduction earthquakes over the past 7000 years. Our event compilation allow us to evaluate the rupture zones of past earthquakes and compare the spatial pattern of paleo-deformation with the contemporary interseismic plate coupling. In the southern margin, the type of geological deformation preserved generally matches that expected due to rupture of the interseismically locked portion of the subduction interface but the southern termination of past subduction ruptures remains unresolved. The pattern of geological deformation on the central margin suggests that the region of the interface that currently hosts slow slip events also undergoes rupture in large earthquakes. Our understanding of subduction earthquake occurrence on the northern Hikurangi margin remains poor, as recent marine terrace studies show upper plate fault deformation dominates the coastal paleoearthquake record. Large uncertainties remain in regard to evidence of past subduction earthquakes on the Hikurangi margin, with the greatest obstacles presented by temporal correlation of earthquake evidence when working within the uncertainties of radiocarbon ages, and the presence of upper plate faults.

Time dependant seismic hazard developments using Coulomb stress changes

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Following major earthquakes, static Coulomb stress transfer (CST) is calculated and used to speculate on the location of possible aftershocks or further damaging earthquakes – this is an example of attempting time-dependant seismic hazard assessment. It is often assumed that the nearest-neighbour fault will have the highest CST and therefore will rupture next. This approach has limited potential to improve seismic hazard assessments; firstly, non-planar faults should be used because the fault geometry affects the magnitude of CST. Secondly, Coulomb pre-stress (i.e. the stress that has accumulated during previous events beyond just the most recent event) is not. These issues present a barrier to the robust inclusion of CST in seismic hazard models (particularly time-dependent models).

We demonstrate a solution to these problems using the 667 years of historical seismicity and interseismic loading in the central Apennines, Italy. We model the CST associated with 34 historical earthquakes and the interseismic loading onto the strike-variable brittle (seismogenic) portions of normal faults. We observe that the next fault that experiences an earthquake is never the fault with the highest coseismic CST. We calculate the “Coulomb pre-stress” prior to each earthquake in the historical catalogue. The magnitude of the pre-stress is ~±50bars, an order of magnitude greater than coseismic CST (~±2bars). Historical earthquakes tend to nucleate in regions of positive Coulomb pre-stress (from coseismic and interseismic loading) and propagate across both positively and negatively stressed regions. These findings highlight the issues of the traditional approach to modelling CST and demonstrate that Coulomb pre-stress is an ignored yet vital factor for earthquake triggering.

Neotectonic fault reactivation and landscape rejuvenation on Norway's post-glacial rifted margin

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The Scandinavian Mountains have been interpreted in terms of normal fault reactivation (Redfield et al., 2005). Seaward-facing linear belts of 'alpine' topographic incision that contrast with landward and high-altitude regions of preserved 'paleic' relief have been described as the product of selective erosion guided by margin-related tectonic processes (Osmundsen et al., 2010). Active normal faulting has been proposed in the Lyngen 'alps' of northern Norway (Osmundsen et al., 2009). The exceptional sharpness and asymmetry of the 'Great Escarpment' in the Møre Trøndelag region also points towards recent fault activity (Redfield & Osmundsen, 2013, 2015). In this presentation we will report on patterns of relief and fluvial incision adjacent to the Møre-Trøndelag escarpment - a region characterized by glacial sculpting, rapid isostatic uplift, and a well-established template of brittle normal faults.

The Surna valley (Surnadalen) of mid-southern Norway is a wide, SW-NE striking, alluvial, U-shaped valley whose SW margin defines part of Norway's Great Escarpment. Surnadalen displays clear morphometric asymmetry: its inland (SE) side is defined by high elevation (>1000 m) and well-developed drainage networks that display clear evidence of alpine glacial carving, while its seaward side is lower (~500 m) and has neither developed drainage networks nor evidence for valley glaciers. Inland drainages display a distinct set of linearly-aligned knickzones, with characteristics inconsistent with transient fluvial response to deglaciation. Incision occurs across fluvial process zones with no correlation to drainage area, suggesting regional forcing rather than catchment-scale drivers. Both lithology and structure are nearly identical across greater Surnadal, and no change in rock type or erodibility correlate with the location or depth of the incision zones. Incision is axially asymmetric: All knickzones occur at the base of the 'Great Escarpment,' and the Tjellefonna Fault Zone (TFZ), the innermost strand of a regionally important fault complex, projects into Surnadal's axis and aligns directly with the knickzone trace. The depth of incision decays from SW to NE in the direction of propagation of the TFZ tip at a mathematically predictable rate. We interpret the knickzone alignment to reflect active normal fault control over incision localization and depth. The depth and morphology of incision suggests Surnadal's incision survived multiple glacial cycles, an interpretation consistent with the assumed 300-500 year repeat interval of Mw >= 6.0 earthquakes. The almost certainly Holocene reactivation of Surnadal's escarpment-bounding faults cannot result from regional tectonic extension. Nevertheless, we suggest Norway's ancestral extensional structural template continues to impose a fundamental control over the creation and maintenance of the Great Escarpment. Post-glacial rebound is likely differentially partitioned across the ancestral faults. So too are tensile, near-surface horizontal fiber stresses generated by both the margin's free face and the changing state of lithospheric flex accompanying geologically rapid loading stemming from onshore erosion and offshore deposition (e.g., the Quaternary NAUST formation). Where pre-existing regional-scale structures such as the Møre Trøndelag Fault Complex are appropriately oriented and positioned, spectacular footwall uplifts may result.

The ~25 ka paleoseismic sedimentary record of the Central Corinth Rift

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Offshore sedimentary cores offer the potential for long, continuous and well-preserved records of past seismic events, and may thus provide important constraints for seismic hazard assessment. The cores of IODP expedition 381 drilled in the Corinth Rift provide an exceptional opportunity to obtain such a record, given their cumulative length (~500-700m at each of three drillsites), high sedimentation rates (~0.5-3 mm/yr), and its location in one of the most seismically active areas of Europe. Here we present our detailed analysis of these cores for the past ~25 ka, in which our primary aims are to 1) identify earthquake-induced deposits and characterise their sedimentological/physical properties, 2) correlate events between the three drillsites and establish a chronology, and 3) understand our results within the framework of the rift's main fault system. We find that the two sites located in the Central Corinth Rift contain abundant homogenite+turbidite (HmTu) layers, which are typical for earthquakes, tsunamis, and landslides. They are easily identified by a combination of X-ray CT-scans, grainsize/–shape analysis and XRF measurements, and to a lesser extent by (the anisotropy of) magnetic susceptibility. We distinguish ~50-70 HmTu layers at both of the sites, and correlate them using their stratigraphic position, chemical signature, and absolute age constraints obtained by radiocarbon and Pb/Cs dating. If all HmTu layers represent earthquakes, the corresponding average recurrence time of ~350-500 years is consistent with estimates for Mw >6 earthquakes occuring along 10-20 km long normal fault segments in the western and eastern Corinth Rift. Comparing our findings to the historical seismic record we discuss rupture scenarios, as well as possible implications for seismic hazard assessment in the Central Corinth Rift.

Damage clustering and fault surface initiation in porous sandstones

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Fault zones in porous sandstone roughly differs from fault related structures in non porous material, and are generally formed of clusters of cataclastic deformation bands into which fault surfaces can be observed. The processes, parameters, as well as geological conditions governing both the development of band clusters and fault surfaces are still unknown and debated. In this study we provide new insights on these processes based on (1) an integrated field and microscopic study of seven sites of different geological conditions (in France, USA, Germany and Scotland), (2) on stress path analysis, and (3) on numerical modeling of inelastic deformation using FLAC.

In agreement with previous works on cataclastic deformation bands, our results based on band cluster analyses reveal that the tectonic loading constrains the extent and the morphology of the clusters. Strain localisation is enhanced in extensional regime whereas strain distribution is favoured in contractional regime. Our analysis of the porosity and shape evolution of the clasts corroborates the hypothesis of strain hardening of the bands by increase of strength induced by the cataclasis. The morphology of the band clusters varies as a function of packing, amount of cataclasis and potential cementation in the deformation bands. Numerical models of deformation band development, consistent with laboratory experiments under conditions around the brittle/ductile transition, show that deformation band damage (band density, thickness of the cluster) is controlled by the cohesion and dilatancy evolution into the bands with respect to inelastic strain. The cohesion and dilatancy functions vary as a function of the applied mean stress and are therefore very sensitive to tectonic regime.

Fault surface development into clusters are observed on a wide range of band cluster thickness and density, suggesting that the increase of cluster thickness does not directly govern fault surface initiation. Our study shows that fault surface localization can be related to larger increase of mechanical contrast between the cluster and the adjacent material, such as resulting from diagenetic hardening of a cluster or juxtaposition of soft material due to clay-smear. Lithological contrasts and diagenesis are favorable conditions for faulting and are independent of cluster thickness.

3D geometry and architecture of a normal fault zone in poorly lithified sediments: A trench study on the Baza Fault, Spain

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The present study describes a 3D outcrop dataset of a normal fault zone in Pliocene-Pleistocene, unconsolidated clastic sediments. The fault zone is on one of the main strands of the active Baza Fault, central Betic Cordillera, south Spain. This fault juxtaposes unconsolidated sediments both in the footwall and hanging wall, leading to the development of a highly complex fault zone structure involving different deformation mechanisms. The fault zone was systematically excavated through a series of 13 trenches, most of them perpendicular to the strike of the fault strand, resulting in a total excavation volume of ~15x15x4 m^3. Walls of these trenches and the excavation floor were interpreted, correlated and integrated to construct a 3D geometric and geological model showing the 3D geometry and internal architecture of the fault zone. This model is an excellent framework for studying the variability of fault zone architecture, mechanisms of deformation, and fault zone evolution. The overall structure consists of two main strands with their respective fault zones. These two fault zones interact and gradually merge to the south, delimiting a main deformation zone (MDZ). This MDZ narrows from ~7 to ~1 m in a distance of ~15 m along strike. Secondary faults in the MDZ accommodate the interaction between the main strands. Fault bounded rock bodies, clay and sand smears, and clay injections define the inner structure of the MDZ. These features, facies and styles of deformation are highly variable and heterogeneous in 3D. We postulate that fault zone geometry, thickness, and symmetry are controlled by the geometry, propagation, and interaction of the fault strands, sediment growth, and mechanical stratigraphy. Mechanical stratigraphy also controls the style of deformation and fault propagation. As the main strands merge to the south and their respective fault zones interact, fault throw increases, deformation is more ductile, and maturity of the structure increases. This shows that the evolutionary stage of the fault zone depends not only of the time elapsed since the onset of deformation, but also on the geometric features of the fault zone. A realistic representation of this 4D picture (if we consider the variation of fault zone evolution along strike) of fault deformation is critical for modelling fluid flow in shallow to possibly deep, faulted sedimentary reservoirs.

Ripplocations: a new mechanism to explain the deformation of phyllosilicates

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Phyllosilicates, such as micas, play a significant role in strain localisation within the lithosphere, owing to their strongly anisotropic, weak, layered structure. Despite their importance, the deformation mechanisms which accommodate this strain have remained ambiguous. Unlike in other minerals, dislocation glide in phyllosilicates is limited to the basal plane with no facility for dislocation motion on other planes, meaning dislocation creep is not a viable deformation mechanism. In addition, kinking, one of the most commonly observed deformation processes in phyllosilicates, cannot be adequately explained by glide of basal dislocations alone. Crucially, there is no existing non-brittle mechanism by which strain can be accommodated perpendicular to to the basal plane (c-axis parallel strain) in phyllosilicates. Recently, a brand new class of defects, known as ripplocations, have been proposed by materials scientists to account for deformation in layered solids. Ripplocations take the form of atomic-scale ripples and enable the motion of one atomic plane over another, as in a dislocation, whilst also containing an element of c-axis parallel strain. They are theoretically applicable to any layered solid, including natural phyllosilicates, but have thus far only been explored within synthetic layered materials. We present the first evidence of ripplocations in natural minerals. We use high-resolution transmission electron microscopy (TEM) to resolve the nano-scale bending characteristic of ripplocations in biotite mica. We demonstrate that conjugate delamination arrays are the result of elastic strain energy release due to the accumulation of layer-normal strain in ripplocations. By invoking ripplocations as a new mechanism in phyllosilicate deformation, we are able to account for several previously unexplained phenomena in phyllosilicates including kink band formation and the pressure sensitivity of mica yield strength at a range of conditions. Ripplocations provide the missing mechanism necessary to fully understand phyllosilicate deformation and may also have as yet unrecognised implications for fields ranging from fault friction to fluid transport in the mid-crust.

Dating faults by K-Ar illite/muscovite geochronology; approach, interpretations and challenges

Invited Keynote Speaker: Espen Torgersen[1,2]

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Ever since the first pioneering observations by James Hutton and Charles Lyell over 200 years ago, it has been the focus of geologists to organize geological events into chronological order. Today, a multitude of geochronometers are available to constrain the absolute ages of a large variety of igneous, metamorphic and tectonic events.

There are, however, few geochronometers that allow for brittle deformation to be dated directly. One of them is K-Ar (and Ar/Ar) dating of illite/muscovite in fault rocks. This method exploits the fact that faulting frequently is associated with fluid-assistant authigenic growth of syn-kinematic minerals, such as illite/muscovite. Although it is analytically a relatively old technique, K-Ar illite/muscovite geochronology has in recent years experienced a renaissance when it comes to fault rock dating, primarily due to the development of new methodological approaches and instrumental progress. Studies published the last decade show the wide versatility of the geochronometer in terms of age of faulting (from Mesoproterozoic to Pleistocene), tectonic setting (compression, extension, strike-slip), temperature conditions (c. 100-300°C) and geographic location (from New Zealand to Northern Norway).

Dating faults by K-Ar illite/muscovite geochronology requires careful interpretations of the obtained ages as fault rocks may be “contaminated” with wall rock-derived, K-bearing minerals, or comprise several generations of syn-kinematic illite/muscovite formed during different fault reactivation episodes. The successful interpretation of obtained fault rock ages therefore depends on an integration of the ages with field- and microstructural observations, mineralogical analyses (XRD, SEM, TEM) and, in many cases, also wall rock thermochronological constraints (muscovite Ar/Ar ages, apatite fission-track ages etc.).

The presentation seeks to give an overview of the K-Ar illite/muscovite geochronometer to those not familiar with fault dating, and to discuss the best-practice for interpreting obtained ages considering those challenges that one may encounter.

Coseismic ultramylonites: evidence of fault weakening by viscous flow during seismic slip.

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Fundamental to understanding earthquakes is the evolution of fault strength at seismic slip rates. In fact, if dynamic weakening occurs in the sliding parts of the fault, less energy is dissipated and more is available for rupture propagation. Laboratory experiments performed on a wide range of rock compositions, representative of those of the brittle crust, show that faults dramatically weaken with slip at seismic slip velocities (> 0.1 m s^{-1}) due to shear heating. However, there is still a lack of understanding of the grain-scale deformation processes that control the weakening of seismic faults. We performed high velocity (1.4 m s^{-1}), displacement-controlled, rotary shear experiments on carbonate powders, a common rock type in many seismically active areas (e.g. Italian Apennines). Our integrated SEM and TEM observations and EBSD analyses show that a switch from brittle (cataclastic) to ductile (viscous flow) processes causes the observed co-seismic weakening (Pozzi et al., Geology 2018). During the early stages of the simulated earthquake, when the fault is strong, we observe that deformation and comminution to nano-grainsize localize into a cataclastic shear band. Here, due to frictional heating, nanopowders start weakening and yielding plastically. At this stage, a strong crystallographic preferred orientation (CPO) develops, suggesting the operation of grainsize insensitive (dislocation) creep. When the fault reaches a very low, quasi-steady state, frictional strength, a fully developed nanocristalline viscous shear zone is formed. Its texture closely resembles that of ultramylonites, commonly found in shear zones in the lower crust. The previous strong CPO becomes weaker, suggesting that a combination of grain boundary sliding, dislocation creep (we have observed dislocations) and grainsize sensitive diffusion creep mechanisms (key to explaining measured low stress levels) control fault rheology. Our findings significantly improve our understanding of the link between fault rheology (e.g. viscous processes) and earthquake rupture processes. Furthermore, our results have implications for the modelling of diffusion creep coupled to intracrystalline plasticity in geo-materials, which has been an intractable problem in geoscience although models already exist in materials science.

Microstructurally-controlled K-Ar geochronology across fault zones

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Brittle fault zones are the dynamic expression of localized slip in response to the accommodation of tectonic stresses in the lithosphere. They are generally composed of a fault core, which accommodates most of the displacement and hosts brittle fault rocks, and an associated damage zone, where the density of brittle deformation features decreases away from the fault core. Studies aiming at constraining the age of movement in brittle fault zones generally concentrate on fault rocks from the fault core, where the K-bearing phyllosilicate illite, which is amenable to K-Ar dating, may form as a syn-kinematic authigenic mineral phase. Illite geochronology is usually performed on multiple grain size fractions of the same fault rock sample and K-Ar data are commonly reported as age-versus-grain-size plots, referred to as K-Ar age spectra. Inclined K-Ar age spectra, with K-Ar age increasing with grain size, are the typical outcome of K-Ar fault rock geochronology and may at times be difficult to interpret.

A detailed outcrop- to microstrucutal study of two fault zones deforming the Ordovician Rolvsnes granodiorite (SW Norway) allowed us to compare microstructurally-controlled K-Ar data from cohesive damage zone samples and bulk K-Ar data from fault gouges from the adjacent fault cores. In Fault I, fluid ingress along the fault core caused pervasive alteration of the host granodiorite. Plagioclase and biotite are almost completely altered to kaolinite, quartz, illite and smectite. In Fault II, a complex deformation history is recorded by multiple fault rock microdomains, including an ultracataclasite with >50 % authigenic illite and an illite/jarosite-bearing pseudotachylyte. Microdomains hosting authigenic illite (± jarosite) from both studied faults were separated, characterized mineralogically and dated by K-Ar. Results confirm that each domain contains only one generation of authigenic illite (± jarosite), and provide robust time constraints on fault initiation in the Carboniferous (331 ± 10 Ma) and reactivation in the Permian (289 ± 6 Ma). K-Ar geochronology of the adjacent fault gouges yields inclined age-versus-grain-size relationships. The ages of the coarsest grain size fractions are similar to the age range of the damage zone data, whereas the ages of the finer fractions are significantly younger (Jurassic and Cretaceous ages, respectively).

Our study provides new and important insights into the dynamics of long-lived fault zones: Isotopic signatures and structural features representative of fault initiation are preserved in the damage zones, while they are progressively overprinted due to cumulative strain localization in the fault cores. Finally, our study further clarifies the significance of “age plateaus” in K-Ar age-versus-grain-size plots.

In-situ U-Pb ages of multiple generations of calcite related to the Ivriz Detachment, Central Anatolia

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Carbonates precipitate in various geological environments including in marine, lacustrine, and hydrothermal systems. Their precipitation as vein filling, breccia cement and fault coating accompanies tectonic processes. U-Pb dating of carbonates is applicable to almost the entire geologic time scale. Associated samples are often texturally complex at the sub-millimeter scale, with either slow-continued or multi-phase growth, making traditional U-Pb bulk analyses in such materials challenging. The *in-situ* approach allows the accurate analysis of crystal subdomains, while ideally avoiding possible mixing or averaging ages of different mineral phases. Combining the absolute ages of such samples with structural analyses contributes greatly to tectonic studies. In the Mediterranean region, such tectonic fabrics are frequently contained in Mesozoic carbonates, which are challenging to date. U-Pb dating of low U-concentration rocks (<10 ppm) has only recently been used for dating diagenesis and deformation structures contained in calcite fibers. The Ivriz Detachment, central Anatolia bounds the Taurides carbonate platform, which in places has undergone HP-metamorphism. This structure played a key role in the exhumation of HP-metamorphic rocks from greenschist-facies conditions by normal-sense structural attenuation of the overriding plate. Related calc-mylonites and calc-schists show semi-ductile to brittle deformation with a normal sense of shear. In this study, we targeted structural domains of several generations of overprinting structures marked by calcite fibers in eleven samples and report absolute ages for diagenetic and subsequent deformation events. The oldest obtained U-Pb ages from the carbonates reflect Mesozoic diagenesis as part of the Tauride platform. A latest Cretaceous-Paleocene age is evident in two samples and overlaps with retrograde phengite $^{40}Ar/^{39}Ar$ growth ages of ∼67–62 Ma assigned to the onset of exhumation of the Afyon HP-rocks. A subsequent extensional event is recorded in six samples ranging from ∼60-56 Ma, consistent with U-Pb crystallization ages from syn-kinematic intrusions of the same age and the main phase of activity of the Ivriz Detachment. Two younger events in Mid to Late Eocene time may be assigned to regional exhumation. The younger of these two events is associated with purely brittle deformation fabrics and may represent final unroofing of the Taurides in the footwall of the Ivriz Detachment. Our results show that in-situ U-Pb dating of calcite fabrics can be successfully used to constrain absolute ages of diagenesis and deformation when put into context with relative constraints coming from field relations and microstructural techniques. Absolute *in-situ* dating of tectonic structures and related overprinting fabrics is vital for comprehending the relative timing, duration and rates of deformation at shallow crustal levels.

Stress permutation during inversion events and the patchy development of structures in orogenic forelands

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Inversion implies a stress evolution in which there is interchange between σ_3 being vertical to cause vertical thickening, and σ_1 being vertical to cause vertical thinning. This interchange will typically involve a phase in which σ_2 is vertical, promoting strike-slip faulting. We link the changes in the magnitudes of stress axes with related changes in fluid pressures (P_f) to understand a common phase of strike-slip deformation between periods of regional extension and regional contraction. This behaviour, illustrated using examples of structures in southern England and the Apennines of Italy, is described because these areas were affected by Alpine contraction, both within areas that did not experience significant crustal shortening and thickening and in more severely deformed orogenic interiors.

We suggest that variable intensity of inversion and related strike-slip faulting across a region is controlled by proximity to the main zone of deformation (e.g. mountain belts) and by crustal strength. Factors that can control crustal strength include lithology, crustal thickness and temperature, relative orientations of stress axes and structures, friction on faults and the occurrence of overpressure. For example, softer overpressured sediments in a warm basin above thinned crust are more likely to be inverted than surrounding basement highs.

Accretionary processes at the northern Australian margin in NW New Guinea – A record of rapid and recent orogenesis

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New Guinea sits at the northern-most margin of the Australian Plate along its contact with the Philippine Sea, Caroline, and Pacific plates. It represents one of the best locations in the world to understand orogensis and accretion. Following the break-up of Australia and Antarctica, the Australian Plate began to move rapidly northwards and subduct beneath the Philippine Sea Plate. Continued plate interaction during the Cenozoic led to the accretion and lateral migration of oceanic (Philippine Sea/Caroline/Pacific plates) and continental (Australian Plate) terranes. The geological record documents multiple periods of island arc accretion, exhumation, magmatism, and major strike-slip faulting.

The Tamrau Block of NW New Guinea represents one of these terranes. In its current position it represents the northern-most extent of Australian continental crust. This terrane block has a complex history – essenially providing a record of the last ~20 Ma of tectonic activity along the boundary between the Australian, Philippine Sea, Caroline and Pacific Plates. The block is an allochthonous crustal fragment situated along a major strike-slip fault zone (the Sorong Fault) between autochthonous stable Australian continental crust and accreted island arcs of oceanic crustal affinity. As such, rocks in the Tamrau Block contain a near complete record of the tectonic activity that has formed New Guinea throughout the Cenozoic. Detailed field studies combined with petrography, U–Pb zircon geochronology, and major and trace element and Sr–Nd isotope geochemisty were used to map rocks of different affinities and to understand the timing and nature of tectonic processes along the northern Australian margin.

Metamorphic rocks in the Tamrau Block record evidence for at least two deformation events, the first is regionally recognised and occurred in the Oligo–Miocene as passive margin sediments entered a north-dipping subduction zone producing amphibolite zone metamorphism. This was followed by a period of middle Miocene volcanism, which produced an island arc along the northern Australian margin and extensive contact metamorphism. Next, middle Miocene sediments deposited coevally with volcanism were uplifted and extensively deformed during the late Miocene–Pliocene as an oceanic island arcs accreted to the northern margin of the Tamrau Block. Finally, comparison of U–Pb detrital zircon ages from sedimentary and metamorphic rocks of the Tamrau Block reveal the block has likely been transported ~300 km westwards along the major Sorong Fault Zone during the Pleistocene as a result of oblique collision between the Australian and Philippine Sea plates.

This presentation provides an overview of the last 20 million years of tectonism at the northern-most point of the Australian Plate. This region records rapid uplift driven by accretion and strike-slip faulting along a system similar in size to the San Andreas Fault. This work demonstrates that mountain building and accretionary processes can occur over a relatively short period. The outcomes of this work can be used to develop a better understanding of ancient accretionary orogens.

Deformation mechanisms in amphibolite-facies ultramylonites associated with pseudotachylytes

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In the Mont Mary unit (Western Alps), pseudotachylytes occur within amphibolite-facies paragneisses strictly associated with ultramylonitic bands and parallel to their foliation. These pseudotachylytes were locally involved in the ductile shearing, apparently under the same high-T conditions as the host rocks, and therefore self-localised thermal runaway is a potential candidate for their development.

We have investigated by Electron BackScattered Diffraction (EBSD) the quartz microstructures of ultramylonite adjacent to pseudotachylyte fault veins, and of quartz clasts included within pseudotachylytes. The aim of the analysis was the recognition of signs of localised accelerated creep rate associated with pseudotachylyte.

The ultramylonite commonly includes layers of fine-grained (average recrystallised grain size of 3-5 μm) quartz, derived from pervasive recrystallisation by subgrain rotation of quartz ribbons, that make transition, through ultra-fine grained aggregates (2-3 μm), to a mixed quartz+biotite aggregate. The transition to ultra-fine quartz initiated at sites of stress concentration (e.g. where sillimanite inclusions where present within the quartz ribbon) and led to the onset of grain size-sensitive (GSS) creep as indicated by the progressive weakening of the strong crystallographic preferred orientation (CPO) typical of the recrystallised ribbons. The transition to quartz+biotite aggregate occur by grain boundary sliding and pore opening in ultrafine aggregates (2-3 μm) along the grain boundaries accommodated by precipitation of biotite. This process was accompanied by progressive randomisation of the CPO. Quartz clasts within pseudotachylyte basically show identical quartz microstructures as the ultramylonite.

The ultrafine recrystallisation of quartz and disaggregation to mixed layers of quartz+biotite represent the most evolved, high-strain microstructural stages of ultramylonites preceding frictional melting. The rate of deformation during quartz disaggregation was controlled by precipitation of biotite in the opening grain-scale cavities and likely by dissolution-precipitation of quartz. Therefore, there is no recorded evidence in the Mont Mary ultramylonite-pseudotachylyte association of coseismic, high-strain rate precursory microstructures to frictional melting. The mixed quartz + biotite layer represent strain-induced weakened portion of the ultramylonite and cannot be totally excluded that they could represent the preserved incipient microstructure that locally evolved into zones of accelerated creep eventually leading to pseudotachylyte. There is no microstructural support to this hypotesis, though.

Ductile shear zones: windows into deformation of lower crust – case study from the Kynsikangas shear zone in SW Finland

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Shear zones contain valuable structural geological information. Utilizing meso- and micro-scale structures together with map-scale interpretations, these features can be used to interpret larger-scale tectonics. The Svecofennian Paleoproterozoic Orogen in Southern Finland provides excellent conditions for interpreting deformation processes at lower crustal levels. The aim of the study of the ductile Kynsikangas Shear Zone (KSZ) is to unravel the Paleoproterozoic structural evolution of the shear zone and show how these kinds of prominent ductile shear zones can be used in the interpretation of the tectonic evolution of the Fennoscandian Shield during the latter part of the Svecofennian Orogeny.

Structural geological mapping, micro-structural and petrographic analyses in combination with anisotropy of magnetic susceptibility (AMS) have been utilized in the study of the KSZ. The study indicates that the core of the shear zone is characterized by steep, N-S to NW-SE striking foliation surfaces, pronounced sub-horizontal mineral stretching lineation, and strongly prolate (L>>S) mineral shape fabrics, together with distinct C-S fabrics. East and west of the shear zone center, the rock is characterized by S>L fabric geometry with moderately to steeply plunging mineral lineations. The km-scale curvature of the foliation surfaces points to an overall left-lateral sense-of-shear during the ductile deformation. However, the shear sense based on small-scale kinematic indicators, rotated rigid objects and asymmetrically folded metamorphic layers are at variance with the first-order kinematics of the KSZ. The AMS data confirms and enhances the field interperation, according to which the magnetic Shape Prefered Orientation (SPO) of the minerals is the same as the metamorphic minerals SPO.

The results points at a more complex deformation and kinematic history of KSZ than what has previously been assumed. The relationship between the shape fabric geometry, its intensity and asymmetric fabrics provide new insights into the structure and rheology of lower crustal shear zones in Southern Finland. The structural and kinematic observations lead authors to conclude that the KSZ formed under two different deformation regimes. Despite complex internal ductile flow, evidenced by the spatial variation in S-L fabric geometry and kinematics of S/C fabrics, the KSZ seems to have accommodated a strong component of left-lateral, pure shear-dominated transpression under roughly E-W shortening. The spatial relationship of metamorphic mineral fabrics and concentration of shear bands in the central KSZ indicate that the deformation is not solely dependent on temperature but it is also due to difference in strain rate. Coupling these observations with the regional tectonic evolution suggest that the collision of two different domains may have led to the activation of the Kynsikangas shear zone in the middle to lower crust during the Svecofennian Orogeny.

Broadhaven revisited: a new look at models of fault-fold interaction

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Coastal exposures of Carboniferous-age strata in SW Wales are recognised for their excellent preservation of Variscan deformation. The classic fold-thrust outcrop at Broadhaven, Pembrokeshire, is a particularly well-known example, and an oft-cited ‘type example’ of fault-related folding, following work by Williams & Chapman (1983). The outcrop has been important for generating conceptual models of fault-fold interaction, and was one of the sites where distance-displacement data were first used to infer thrust slip/propagation ratios. Here we employ the virtual outcrop method to digitally map and measure this classic locality. 3D reconstruction of the outcrop by digital photogrammetry allows us to extract high-density structural measurements, reassess the existing model of structural development, and re-evaluate the link between faulting and folding at the site.

We find that high-resolution digital measurements record greater variability in thrust displacement and bed thicknesses than previously documented at the site. Distance-displacement data record the influence of mechanical anisotropy on slip/propagation ratios through the deformed multilayer. Bed thickness changes are linked to this variability in thrust displacement, highlighting transitions in strain accommodation patterns. Fracture analysis shows that fracture intensity is closely linked to structural position and bed thickness changes, and that fracture orientations record the existence of discrete mechanical boundaries through the structure. These results record complex patterns of strain distribution and multi-phase deformation. Evidence for temporal and spatial variability in strain distribution suggests that multiple kinematic and non-kinematic models of deformation are required to faithfully describe even this apparently simple structure. We use this detailed field evidence to propose an alternative to and develop, for multi-layered stratigraphy, the ductile bead model of Elliot (1976), as exemplified at Broadhaven by Williams & Chapman (1983).

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How complex structures affect thermal maturity indicators: a case study from the Haut Giffre, French Alps.

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It is well-known that the thermal maturity of carbon-bearing rocks increases with burial depth, and that over-thrusting creates thermal anomalies by burying and insulating the units below the thrust. Additionally, friction along an active thrust plane imparts further heat into the surrounding rock, but this thermal effect is not well understood.

This study investigates the extent of localised thrust-related thermal anomalies by applying Raman spectroscopy to Jurassic-Cretaceous marls in the Haut-Giffre region (French Alps). Raman spectroscopy of organic carbon within the marls is used as a thermal maturity indicator. Raman analyses back-scattered radiation from individual carbon grains to produce a spectral curve with 2 or more “peaks”. The width and spectral shift of these peaks is determined by the molecular structure of the carbon, which can be related to thermal maturity, and can be used to predict a maximum temperature for the sample.

Raman spectroscopy was carried out on samples taken from vertical transects crossing thrusts and folds, spanning 1800m of thrust-stacked stratigraphy. A trend of decreasing thermal maturity towards higher levels in the thrust stack was observed. Local thermal anomalies were also found; elevated thermal maturity indicators were associated with proximity to thrust faults. The magnitude and extent of the anomaly was found to be greater around regional thrust faults (e.g. 500m displacement) than their minor counterparts (e.g. 2m displacement).

In the case of a tight recumbent fold on a 100m-scale, with interlimb angles of <15°, the paired fold cores contained similarly tight parasitic folds an order of magnitude smaller, and mylonitic zones in the lower hinge of the overturned limb. Raman spectroscopy across the major recumbent fold showed that the characteristic core structures (internal folds and mylonite zones) indicated elevated thermal maturity, which would imply a higher maximum predicted temperature, compared to the upper and lower limbs of the major fold.

The exact cause of the anomalies is unclear; although frictional heating along the fault plane may be responsible, it is possible that hot fluids may also use these deformation zones as a conduit, imparting heat into the surrounding rock. Alternatively, shear-ordering of carbon nanostructures, changing the molecular structure of the carbon during thrusting, may produce the spectral signal, rather than heating. Irrespective of the mechanism, the observation that thermal maturity does not vary linearly with burial depth – and instead may be locally elevated by thrust faults (regional or local) or folding – has important implications for predicting the maturity (or over-maturity) of source rocks in compressional regimes.

Structural reworking of the lower crust during Caledonian nappe emplacement in Arctic Norway

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The Kalak Nappe Complex (KNC) of the Norwegian Caledonides in the area of Hammerfest (Kvaløya Island, Finnmark, Norway) is characterized by a series of mid and lower crustal slices that experienced a prolonged deformation history. Through field- and micro-structural analysis, thermodynamic modelling and geothermochronology we aim to: (i) disentangle the tectonic history of the KNC in Kvaløya; (ii) define the different deformation and reworking styles related to the Caledonian orogeny; (iii) investigate the processes contributing to nappe staking in the lower crust at the orogen scale.

In the northern Kvaløya, the Sværholt Terrane includes the Smørfjord psammite placed at the core of a steeply inclined NE-SW-trending and SE-verging tight syncline, at whose limbs the Fagervik banded gneisses occurs. Fold axes and stretching lineation are NE-SW-trending and shallowly plunging.

The Sørøy Terrane, composed of Eidvågeid migmatitic paragneisses and overlying Klubben Psammites, crops out in the central Kvaløya. A bulk shallowly NW-dipping foliation, developed at (pre-Caledonian) melt-present conditions, characterizes the Sørøy Terrane. The Sørøy Terrane overthrust the Sværholt Terrane to the south, which crops out again in Southern Kvaløya, consistently to the regional top-to-SE Caledonian transport direction. The Southern Sværholt Terrane is characterized by an anastomosing thrust-parallel foliation, with NW-plunging stretching lineation and wrapping around NW-SE-trending curtain folds with foliation-parallel fold axial plane.

Caledonian thrusting developed at 550-675°C and 0.75-0.95 GPa. Preliminary Ar-Ar dating on white mica and biotite suggests Caledonian cooling ages for migmatitic Eidvågeid (430 Ma); whereas, for thrust rocks it suggests a prolonged tectonometamorphic history lasting from 980 to 480 Ma.

Caledonian re-activation of pre-existent bulk fabrics occurred only where fabrics were optimally oriented for thrusting (e.g. NW-dipping Eidvågeid foliation), whereas folding interference patterns developed in “banded” units (Sværholt Terrane). The geometry of the interference pattern differs according to the relative orientation between pre-existing folds and Caledonian thrusting direction.

3-D structural uncertainty in seismic interpretation: A case study on the Gullfaks fault block

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In recent years uncertainty has been widely recognized in geosciences, leading to an increased need for its quantification. Predicting the subsurface is an especially uncertain effort, as our information either comes from spatially highly limited direct (1-D boreholes) or indirect 2-D and 3-D sources (seismic). And while uncertainty in seismic interpretation has been explored in 2-D (Bond et al. 2007; Bond 2015; Alcalde et al. 2017), we currenlty lack both qualitatitive and quantitative understanding of how interpretational uncertainties of 3-D datasets are distributed.

In this work we analyse more than 90 seismic interpretations done by fourth year, final year Scottish undergraduate (BSc), students of a 3-D seismic dataset from the Gullfaks field. It is located in the northern North sea as part of an array of NNE-SSW-trending domino fault blocks eroded by the Base Cretaceous Unconformity (Fossen and Hesthammer 1998). The students used Petrel to interpret multiple (interlinked) faults and to pick the Base Cretaceous Unconformity and Top Ness horizon (part of the Mid-Jurassic Brent Group). We have developed open-source Python tools to explore and visualize the spatial uncertainty of the students fault stick interpretations, the subsequent variation in fault plane orientation and the uncertainty in fault network topology. The Top Ness horizon picks were used to analyse fault offset variations across the dataset and interpretations. We investigate how this interpretational uncertainty interlinks with seismic data quality and the possible use of seismic data quality attributes as a proxy for interpretational uncertainty. We additionally demonstrate methods to best visualize and summarize complex interpretational uncertainty in 3-D.

Our work shows the extent of interpretational uncertainties in a 3-D seismic dataset, and could serve as an upper limit to inform efforts in quantifying uncertainty in interpretation of North Sea seismic data. We aim to further use the results, and other studies, to serve as a valuable input into stochastic modeling efforts to quantify the effect of 3-D seismic interpretation uncertainty on structural models of the subsurface.

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Structural controls on fault and top seal. Insights from analysis of column height data from the Snøhvit gas field in the Hammerfest Basin, SW Barents Sea.

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Faults act as pathways or barriers to fluid flow and so profoundly influence subsurface fluid migration, accumulation, retention and leakage. Assessment of the retention/seal risk of structural hydrocarbon traps depends upon robust knowledge of the capacity of faults to seal or leak fluids. Faults commonly exhibit spatial variability in sealing properties, and can alternate between being transiently sealing and leaking through time as the fault undergoes dynamic changes in deformation, diagenesis and applied regional or local stresses. However, the range of factors that affect fluid flow at faults and fault intersections are often neglected by common methods that attempt to predict hydrocarbon column heights. One such method assumes that hydrocarbon leakage only occurs when the top seal mechanically fails. This occurs when the pressure of the hydrocarbon and underlying water column exceeds the fracture strength of the cap rock to form new permeable tensile fractures, which act as conduits for fluid flow. To test the reliability of this predictive method, 18 discovered hydrocarbon columns, all targeting structural traps, were measured across the Hammerfest Basin. Results show that firstly, measured in-place column heights are consistently and significantly lower than those predicted using the mechanical strength properties of the cap rock. Secondly, the measured column heights indicate that all of the structural traps are underfilled, that is, none of the traps are filled by hydrocarbons to their structural capacity. These results suggest that mechanical failure of the top seal is not the key control on hydrocarbon leakage. Therefore, other causes of trap underfilling must be explored.

One possible cause of trap underfilling is an initial lack of charge. However, in all 18 measured wells, paleo-oil shows are present at depths below the measured hydrocarbon-water contact. This is a strong indicator that that the structural traps were previously well-filled and subsequently leaked by either across- or top-fault breach, resulting in underfilling. To investigate across seal-breach by capillary entry pressure, fault-seal analysis was performed on five structures within the Snøhvit gas field. Results indicate that the major bounding faults have high capillary entry-pressures and are capable of sealing significantly taller hydrocarbon columns than discovered. We therefore believe that leakage has not occurred by across-fault breach but by top-seal breach. Current work is now focusing on how fault intersections and fault reactivation contribute to top-seal breach. It is well known that fault intersections are associated with higher deformation and commonly form foci for fluid flow. Results from throw-depth profiles (T-z plots) indicate that a number of faults have been reactivated at a time that post-dates the charge event from the main source rock, the Hekkingen formation. We believe this begins to offer good evidence for vertical leakage by top-seal breach. Further work aims to understand how fault reactivation at sites of fault intersection correlate to measured hydrocarbon column heights. Such work will help to elucidate locations of enhanced fluid flow, leading to better estimations of top seal risk and hydrocarbon column heights during prospect analysis.

How do survey parameters affect the imaging of normal faults? A case study from the Snøhvit Field, Barents Sea

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The seismic imaging of faults has been a key topic of conversation in both academia and industry for decades. We present a series of observations aimed at understanding the seismic expression in and around faults. We apply well-known techniques in seismic analysis to Ocean Bottom Seismic (OBS) in both the PP and converted-wave (PS) domains from the Snøhvit Field, Barents Sea. The data (PP, PS) were acquired in two directions (E-W, W-E) and is available in near, mid, far and full angle stacks in each direction. This makes for a total of 16 seismic data volumes analysed in this study. The data were conditioned by filtering noise in two stages (SOFHM and TDiff). Filtering was implemented with special care to maintain the signal on and surrounding faults. After data conditioning, a comparison of the imaging of faults in PP and PS data was completed by analysing seismic attributes in both W-E and E-W directions. In the Snøhvit Field area, it was found that the seismic imaging of faults in PP and PS data are both successful, but the PS data had better signal-noise ratios due to the minimal effect of the gas cloud. The extent of the shallow gas and its effect on the seismic imaging of faults was assessed using the PP and PS data. The orientation/shooting direction also plays a key role in imaging faults. For analysing the impact of the shooting direction, we only focused on the PS data as they had the best fault imaging. There are two main faults in the imaged area, a northern and a southern fault. The northern fault strikes NE-SW and appears to be segmented into two. The southern fault strikes approximately E-W and doesn't appear segmented. The imaging of the southern fault doesn't change much with respect to the survey shooting direction (likely because the fault is oriented along the survey) while the northern fault's imaging is influenced (it is more orthogonal to the survey orientation). The imaging of the northern fault is clearer in the E-W survey direction, the reason for this is likely related to the undershooting of the fault. The next process is the analysis of angle stacks by generating single attribute CMY colour blends (tensor, semblance, dip, RMS amplitude and fault enhancement) containing the near (C), mid (M) and far (Y) offset data of the PS data in the E-W and W-E directions. The results of this step show imaging variations surrounding the faults in all attributes and major imaging differences with shooting directions. This confirms that faults are imaged slightly differently in each angle stack volume, with each attribute and with survey direction. Finally, high definition frequency decomposition shows that the low and medium frequency bandwidths (15 and 22 Hz) are much more successful at imaging the faults in this area than the highest frequency (29Hz). This result is expected as the faults in this study are prominent at ~2000ms and lower frequencies are able to penetrate deeper into the subsurface. The frequency content in the E-W survey is much clearer at imaging faults than that of the W-E survey, this is again likely due to undershooting, but it needs to be further investigated. These three analyses improve our understanding of how seismic survey type, shooting direction and frequency content impact the imaging of faults in the subsurface and can ultimately help understand what information is contained in the data or even how to improve the survey design.

The SAFARI database and 3D web viewer: a new way of sharing outcrop data

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The SAFARI Project is a research initiative to compile and interrogate a diverse range of data on geological outcrops for hydrocarbon exploration and production, which has been running for about 30 years. The project has developed into a cloud-based, searchable repository of outcrop data, the SAFARI database, accessible today at http://SafariDB.com.

In addition to general descriptions for each geological outcrop, the SAFARI database stores detailed work carried out at a locality by individual researchers as studies, allowing multiple investigations and results, potentially by different geologists or groups, to be published. For each outcrop, the SAFARI database can include measurements, maps, field photographs, logs, cross-sections, interpretations, diagrams and figures, as well as high-resolution virtual outcrop datasets. Key to the database design is the ability to query the stored outcrops using a hierarchy of metadata (SAFARI standard) with which each outcrop is tagged, including such parameters as geological age, basin type and depositional environment. Users can use filters to browse and refine the list of stored outcrops.

Central to the SAFARI database is a purpose-built 3D web viewer for viewing virtual outcrop models representing a stored outcrop section that has been acquired using laser scanning or photogrammetry. A key feature of the web viewer is the fast streaming of extremely large and detailed outcrop sections over the internet. In addition, interpretations can be overlain on the 3D models as additional texture layers, and toggled interactively using a transparency slider.

At present, the SAFARI database hosts descriptions of more than 300 clastic sediment outcrops, many of them also containing a virtual outcrop model. In 2019, the database will be expanded to also cover structural outcrop localities. The contribution of this presentation is to present the SAFARI database as a leading repository for geological outcrop data, especially virtual outcrops. A significant proportion of SafariDB is being made public with the aim of offering the database as a public resource for the wider geological community to share the wealth of data that are now being collected.

Fracture network characterization and two-dimensional connectivity in geothermal reservoir analogs: Multi-scale investigations from the Sotra Islands in Norway

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The Sotra islands in western Norway provide good exposures of heavily fractured crystalline rocks, suitable analogs to naturally fractured reservoirs in conventional and enhanced geothermal systems. Well-exposed outcrops allow for semi-continuous sampling across several scales of observation, providing insights to fill imaging gaps that exist between well data and geophysical methods in subsurface reservoirs.

Our study used fracture networks in the Algerøyna and Vikso sectors of Sotra, digitized over images with variable pixel resolutions to capture similarities and differences across scales, from drone photography, satellite imagery and digital elevation models (0.1 to 50m pixel size). This resulted in fracture sampling over several scales of observation, three for Vikso (1:10 to 1:1000) and five for Algerøyna (1:1 to 1:10000).

Two-dimensional connectivity was first assessed using topological methods, which were further compared with critical percolation parameters, as well as explicit Discrete Fracture Matrix (DFM) simulations of fluid and heat transport for the different networks.
Statistical distribution of fracture lengths follow similar power laws and coefficients across scales, as well as topological signature (i.e. all datasets capture similar parameters regardless of scale resolution). On the other hand, geometrical differences are captured across scales, in the form of orientations and spatial distributions within each domain. Percolation analyses show some scales with clear percolation potential whereas others fall at the percolation threshold. Preliminary results from DFM simulations also indicate differences in flow behavior between scales of observation.

Our results show a self-similarity of both topology and length distributions over several orders of magnitude, though the specific geometry of each network and therefore its flow behavior display differences across scales. This can have important implications in the application of different parameters while upscaling fractures in reservoir modelling and the subsequent estimation of flow effects from sub-seismic fracturing.

Storage and migration properties of fractured carbonate reservoirs, insights from the analysis of surface structural analogs

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Worldwide, fractured carbonate reservoirs host in the underground significant amounts of freshwater, mainly used for food production, and ca. 50% of the whole oil and gas reserves. Furthermore, depleted oil and gas carbonate reservoirs might form preferential sites for subsurface CO_2 storage, which is envisioned as a common practice to decrease the greenhouse gas concentration in the atmosphere. Accordingly, there is today a growing need for a better understanding of the control exerted by depositional, diagenetic and deformation processes on the petrophysical properties of fractured carbonates. This contribution focuses on the fracture stratigraphy of Cretaceous limestones of the Apulian Platform, which are currently exposed in both inner chain and foreland domains of the Apennines ftb, Italy. First, composition, texture, effective porosity, pore type and pore geometry of the study limestones are assessed by considering the results of combined petrographic and petrophysical analyses. Both nature and dimensions of primary heterogeneities are also taken into account. Then, both dimensional properties and multi-scale distributions of joints, sheared joints and small faults that crosscut large-scale rock volumes are documented, and their distribution discussed in light of the diagenetic evolution of the study limestones. Finally, the results of Discrete Fracture Network modelling of representative geocellular volumes, which is aimed at computing the amounts of fracture porosity and equivalent permeability, are interpreted in terms of their storage and migration properties. This work hence emphasizes the role played by the primary architecture of fractured carbonates on the flow and accumulation of geofluids in the subsurface.
It is documented that both bed-perpendicular joints and sheared joints form the main control on fracture porosity. Due to their pervaisiveness, these structural elements form well-connected, diffuse networks within the limestones. Joints often abut against laterally discontinous bed interfaces, and therefore form stratabound networks within mechanical units, the single beds, as thick as several 10’s of cm. Of course, the pronounced bed amalgation quite obliterated the original limestone configuration, so that smaller scale mechanical units are also depicted within single beds. Sheared joints are interpreted as incipient, high-angle faults made up of throughgoung slip surfaces flanked by very discontinuous fragmented limestones, which form non stratabound networks within a few m-thick mechanical units, the bed packages. The bed-packages are bounded by 100 m-wide, transgressive erosional surfaces, which include cm-thick clayish material and form sequence boundaries of the 3rd order. At a larger scale, the km-wide, prominent transgressive surfaces that actually consist of cm-thick volumes of collapsed breccias and terrigeneous material are interpreted as sequence boundaries of the 2nd order. These prominent primary heterogeneities bound ca. 50 m-thick bed package associations, and constitute very efficient mechanical interfaces for the vertical growth of small faults made up of continuous, 10’s of cm to m-thick, fragmented and brecciated limestones. These small faults crosscut and displace multiple transgressive erosional sequences, and form the preferential sites for geofluid migration within rock volumes bounded by seismic-scale fault zones.

Impact of faults on CO_2 Storage Capacity and Leakage Risk Assessment: Key Learnings from Smeaheia, off-shore Norway

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Understanding of faults in CO_2 Storage projects is crucial since faults can largely impact the project in 1) across-fault migration/leakage risking, 2) along-fault migration/leakage risking, and 3) reservoir pressure prediction. Fault consequently serves as a key factor for estimating the storage capacity and leakage risks, given CO_2's unique physical properties and flow behaviors in subsurface conditions.

At the same time, CO_2 Storage projects also carry some distinct features that provide new challenges for structural geology analysis, including a) ~1000 year (forward) time-scale for storage, which is different from either exploration (i.e., geological time-scale: ~myr) or typical development (i.e., production time-scale: ~20-50 yr) projects in O&G industry; b) Published regulations and standards require clear demonstration of CO_2 confinement and conformance risks in an As Low As Reasonably Practicable (ALARP) level; c) Public sensitivity and communication issues.

Smeaheia was evaluated as a storage candidate for Norway's first full-scale CCS project called Northern Lights. It is a fault block seated to the east of Troll East field, bounded by Vette Fault Zone (VFZ) to the west and Øygarden Fault Zone (ØFZ) to the east. The primary storage unit is the Jurassic Viking Group sandstones. Two storage prospects in Smeaheia—namely Alpha and Beta structures—are not hydrocarbon-charged based on previous drilling results.

After integrating off-shore datasets and on-shore geology of Bergen area (e.g., outcrops, tunnelling and water wells), our investigation suggests that the Beta structure shows high across-/along-fault leakage risks, and thus is not suitable for large-quantity in-place CO_2 injection and storage, because: a) It is a down-thrown 3-way closure against ØFZ, with the structural high directly juxtaposed to the faulted/fractured (and potentially weathered) basement (i.e., Øygarden Complex–ØC); b) ØFZ has small fault throw around the structural high of Beta which implies sand-rich fault rocks—thus higher fault rock permeability; c) Its present-day structural shallowness (i.e., ~800 m TVDSS) is unfavorable for CO_2 to maintain liquid or supercritical phases; d) ØFZ has braches potentially reached to the seabed to the north of the Beta structure, while the fault linkage is uncertain due to lack of seismic reflections in the crystalized basement; e) Recorded earthquakes, albeit with low magnitudes (i.e., commonly < Ms 4.0), imply active faultings around the ØFZ and ØC areas.

The Alpha structure shows relatively low fault leakage risks. It is an up-thrown 3-way closure against VFZ, and it shows numerous geological similarities with those fault blocks in the Troll field that trapped hydrocarbons. However, fault seal study results of Viking Group sandstones on several relay ramps along the VFZ show a high risk of pressure communication between the Troll field and Alpha structure (and Smeaheia in general)—thus the pressure draw-down from the Troll field is considered a major risk to the storage capacity of Smeaheia. Here we list key geological uncertainties and modelling challenges in the pressure prediction of Smeaheia within the 1000-year time range, as well as strategies for futher maturing this storage site.

This study summarises key learnings from Smeaheia and illustrates the importance and challenges of structural understandings on screening and development of future CCS projects.

Development of stress enhanced tensile fractures in elliptical clast in conglomerate: rheological, geometrical and mechanical constraints

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Mode-I fractures within the elliptical clasts of three Neoarchean conglomerate beds from Archaean age Chitradurga Schist Belt (Dharwar Craton, South India) are analyzed to decipher the paleostress condition. These fractures are characterized as systematic, steeply dipping and parallel to each other. The analysis is performed in three steps – (1) fixing and transforming of the coordinate systems to describe the elliptic domain under far-field stresses, (2) proposing suitable complex potentials for a single inclusion embedded in an infinite matrix, followed by the application of plane strain solution for elliptical domain to model the fractured clasts, (3) obtaining the state of stresses readily inside the inclusion.

We conclude that the mode-I fractures in elliptical clasts have developed due to enhancement of far-field stresses inside the rigid clasts at shallow depth (~2 to 4 km). The deduced paleostress conditions also accommodate the orientation of the previously revealed regional tectonics. We infer that the amplification of stresses in the rigid inclusions is a function of elastic moduli, remote stresses and ellipticity of the clasts. We interpret that the enhanced intra-clast differential stresses are related to clasts with higher aspect ratios, which are more susceptible to tensile fracturing than clasts that have lower aspect ratio (for any constant applied far-field stresses). We also estimate the minimum breakage loads as well as minimum depths, required for the clasts of different aspect ratio to develop tensile fractures. The conglomerates we observed showed two types of clast congestion: tight and loose embedding, which displayed significant deviation in fracture frequency and aperture. Furthermore, to make the approach more robust and realistic, we performed a similar analysis for a multi-clast arrangement whilst considering multiple scenarios with respect to the clast positioning and congestion in the matrix.

We observed that the stress enhancement within the central clast of a congested scenario differs from that within a single clast, a result of the so-called “shielding” effect. Additionally, we infer how the degree of congestion influences this “shielding effect”. Therefore, we conclude that fractured elliptical clasts can be regarded as an important paleostress indicator.

Middle Jurassic and Early Cretaceous rifting events in the South-East of the Mesopotamian Basin, South-East Iraq: evidence from subsidence analysis

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The Mesopotamian Basin is a wide (~200 km by ~800 km) petroleum rich sedimentary basin whose evolution is poorly understood, particularly during the passive margin setting, mainly due to limited subcrop data. In this study, subsidence analysis has been carried out on fifteen wells which penetrated through Cenozoic and Mesozoic successions down to the Middle Jurassic strata, to provide insights into the main tectonic events that have influenced the basin's evolution during the passive margin setting. The passive margin setting, from the Permian to the Late Cretaceous, represents a significant part of the basin petroleum system. Results from the subsidence analysis reveal distinct tectonic phases of rifting during the Middle Jurassic and the Early Cretaceous. The first rifting phase occurred ~165 Ma and started with a high tectonic subsidence rate that decreased exponentially during the postrift thermal subsidence. This event stretched the lithosphere with a β factor of 1.3 to 1.4. After a hiatus in ~150 Ma, the tectonic subsidence rate began to increase gradually in most of the study area due to a local flexural event. Thereafter, the tectonic subsidence rate decreased to a trend similar to the previous postrift subsidence. This indicates the ending of the local flexure at ~140 Ma and the continuation of the thermal subsidence that eventually ceased by ~135 Ma. At around 130 Ma, the decreasing pattern of the tectonic subsidence rate suggests another phase of rifting that was shorter and less intense than the previous rift and stretched the lithosphere with a β factor of 1.1 to 1.2 with postrift thermal subsidence finished by ~115 Ma. There was not an evident tectonic event until ~95 Ma when a flexural phase initiated. Comparing these results to the more recent geodynamic studies (e.g. Jolivet et al., 2016; Nouri et al., 2016) shows that these rifts belong to the rifting episodes which opened and expanded the southern branch of the Neo-Tethys Ocean. This narrow branch closed with the ophiolite obduction which most probably caused the last flexural event in ~95 Ma and ended the passive margin setting for the northern margin of the Arabian Plate. This study presents clear evidence for tectonic influence of this rifting on the Mesopotamian Basin. Performing subsidence analysis on the other parts of the Mesopotamian Basin and the surrounding terrains will unveil more details of tectonics of the northern passive margin of the Arabian Plate which will lead to a more realistic regional petroleum system model for this petroleum rich region.

Geomechanical and Petrological Characterisation of North Sea Reservoir and Caprock Lithologies; Potential for Offshore Carbon Capture and Storage in the United Kingdom

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Extraction or injection of fluids within a petroleum system causes fluctuation of fluid pressures and the resulting stress conditions. If the yield strength of the reservoir or caprock lithologies are overcome by these fluctuations, the system could be potentially compromised through compactional or dilatational failure. The yield strength of a rock is fundamentally controlled by its mineralogy and texture, i.e., the chemical composition of its constituent minerals and the way they are fitted together. It is paramount to have knowledge of the geomechanical strength of a system's lithologies, and the factors that control it in order to maintain optimal conditions during extraction/injection.

A novel, experimental, geomechanical and petrological investigation has been performed on two potential CO_2 geological storage sites off the coast of north east Scotland. This investigation was instigated by the ACT Acorn CCS project, funded by BEIS (UK), RCN (NO), RVO (NL) and ERA-NET under the Horizon 2020 programme, which aims to implement a low-cost, scalable, full-chain industrial CCS project by 2022.

In order to confirm the geomechanical and petrological suitability of the proposed CO_2 storage sites, the Acorn CO_2 Storage Site and the East Mey Storage Site, the reservoir and caprock lithologies of each site have been characterised using a suite of techniques. These include: the experimental measurement of the splitting tensile strength and yield behaviour at varying fluid pressures and specimen porosity, in combination with optical microscopy, quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN), X-ray diffraction, mercury porosimetry, and well logs to determine their petrological character.

Both the Acorn and East Mey CO_2 storage sites have highly porous and transmissible sandstone reservoirs, with bulk mineralogies that are stable under CO_2-rich conditions; these make the sites ideal for receiving and containing the proposed quantities of CO_2, 152 MT (5 MT/yr injection rate) for storage for a minimum of 1000 years. However, due to the high porosity and low cementation of these sandstone reservoirs, they have low yield strength and are vulnerable to disaggregation and porosity reduction if stress/pressure conditions exceed their yield strength. The shale caprocks from both sites have high swelling clay content, very low porosities and exhibit typical yield strengths for shales. This study has constrained the optimal operating pressure/stress conditions of the proposed sites and the lithological factors controlling them.

Unravelling the relationship between thrust and sinistral shear in the Shetland Caledonides

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NW Shetland occupies an important location linking the pre-Permian rocks of Shetland with the Precambrian and Caledonian orogens of mainland Scotland, Norway and Greenland. In Shetland, Archaean orthogneissic basement and Proterozoic metasediments are transected by the major strike-slip Walls Boundary Fault (WBF) and the Wester Keolka/Uyea thrust fronts, the supposed northern continuations of the Great Glen Fault and Moine Thrust respectively. Despite this critical location, Shetland remains poorly understood, as relatively few modern, systematic geochronological studies have been carried out in conjunction with detailed structural and metamorphic mapping.

Recent mapping of ductile and brittle structures in NW Shetland reveal a series of distinct east-dipping structural domains, from west to east as follows. The structurally lowest domain immediately above the Uyea Shear Zone comprises reworked 'foreland' Archaean orthogneisses that display a complex history of extensional and strike slip shear along NE-SW shear planes. Overlying orthogneisses of probable Archaean age show intense strain and evidence for top-to-the-NW thrusting. Published Rb-Sr white mica ages of 427 and 412 Ma from these domains suggest a late Silurian to early Devonian age of shearing (Walker *et al.* 2016). Separating the orthogneissic basement from the metasedimentary Sand Voe Group (=Moine?), the Wester Keolka Shear Zone (WKSZ) may be a localised basement-cover high-strain zone rather than the extension of the Moine Thrust. Within the WKSZ, ductile fabrics have yielded Rb-Sr white mica 'Knoydartian' ages of *c.* 720-702 Ma (Walker *et al.* 2016). In the WKSZ and overlying Sand Voe Group, stretching mineral lineations swing from plunging moderately ENE along the WKSZ, to shallowly-plunging NNE in the centre of the Sand Voe Group, before swinging clockwise to moderately-plunging E. Structurally above this, amphibolite intrudes the Sand Voe Group and displays top-to-the-NW thrust shear sense. This domain is overlain by the Queyfirth Group (=Dalradian?) mica schists and psammites that display a top-to-the-N sense of shear on sub-horizontal to gently-east-dipping foliation planes. The WBF transects the Queyfirth Group, recording sinistral Silurian-Devonian offset at upper greenschist/lower amphibolite facies metamorphism, before being dextrally reactivated during the Carboniferous (Watts *et al.* 2007).

NW Shetland records a complex multi deformation Archaean to Mesozoic history, yet key components remain enigmatic. At what temperature have the orthogneisses and metasedimentary cover been metamorphosed? What are the ages of the metamorphic and deformational events in the 'foreland' and metasedimentary cover? What is the relationship of the WBF to the deformation observed on NW Shetland? A detailed microstructural study, quartz c-axis geothermometry, Rb-Sr and K-Ca dating of white micas and further fieldwork will aim to constrain these questions and compare the tectonic events observed in Shetland against those in mainland Scotland, Norway and Greenland.

Principal slip zone characterisation in natural basaltic faults

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The mechanical and hydraulic properties of fractured and faulted basaltic rocks are key to predicting the effects of natural or induced fluid flow and variations to the stress field in volcanic lithology dominated regions. Fractures and faults introduce heterogeneity, notably as zones of weakness (joints, veins, breccias, cataclasites, slip surfaces), and may focus fluid flow, mediating mineralogical alterations that replace strong crystalline rock by weak and interconnected clays. As volcanic rocks are a prime target for geothermal energy production, deeper understanding of natural fluid-rock interaction and the resulting products, will help to improve energy extraction, risk assessment for natural hazards, and carbon storage potential.

For this project we will study exceptionally well preserved fault rock assemblages derived from basalt lavas on the Faroe Islands. Initial results from thin section analysis show progressive strain accumulation and localisation initially manifesting in breccias, followed by calcite and zeolite veins, and finally cataclasites. The fabric evolution is accompanied by nearly complete replacement of the original mineral assemblage in the cataclasites that form the fault core, grading into better preserved assemblages in the surrounding breccias.

These findings will be complemented by a characterisation of fault zone topology and complexity in the field. Moreover, fabrics and mineralogical composition will be analysed in fault core material. These will then be correlated to mechanical properties determined in triaxial deformation experiments, dynamic permeability evolution during deformation as well as directional permeability along and across the slip zone. Acoustic emission transducers will monitor strain localisation and subsequent fracture development during the deformation experiments. Pre- and post-deformation fabrics in the cores will be compared through CT scans.

Fracture corridors and low-offset faults in basement rocks and their influence on reservoir properties and performance

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Fracture corridors are tabular zones of closely spaced fractures that exhibit limited or no shear offset. Fracture corridors are generally hard to detect using reflection seismic imaging due to their lack of shear offsets, and few boreholes transect these zones in the subsurface. Despite being common and potential high-permeable fluid conduits, fracture corridors have received less attention than faults. Here, we present outcrop observations from metamorphic, volcanic and sedimentary rocks in Norway and Mexico that suggest these zones can be laterally continuous up to tens of kilometres, and exhibiting widths of up to 60 metres. The fracture corridors are commonly laterally segmented, and may exhibit internal brecciation, clay fill and may be associated with dissolution features (karst) and/or mineralization.

The fracture corridors studied in the outer coastline of Norway are hosted in Proterozoic gneisses and Silurian granites, and are up to 10 kilometres long and between 0.4 to 60 metres wide. These zones are part of conjugate network of NE-SW and NW-SE trending fracture sets and faults formed during multiphase tectonic activity in Paleozoic to Cenozoic times. The fracture corridors studied in Mexico are hosted in Mesozoic limestones and Miocene volcanics and formed during Laramide folding and Miocene to recent transtensional tectonics and caldera collapse.

The studied fracture corridors have been mapped in detail using high-resolution photogrammetry and structural outcrop data, characterizing the spatial distribution of the fractures. Results suggest that the studied fracture corridors exhibit fracture frequency that is on average six times higher than background fracture frequencies. Fracture connectivity within the fracture corridors is also significantly higher than surrounding rocks. Interestingly, individual fracture length does not seem to be greater than the background area, however due to higher degree of segment linkage the combined length of linked segments is significantly higher compared to background areas. Fracture corridors in sedimentary and foliated rock have higher frequencies than massive unfoliated rocks.

Fracture corridors may be found in all types of tectonic settings, but their geometry, architecture and flow properties are poorly understood. In this ongoing work we are developing a better understanding of these structures, their properties and distribution, with the ultimate aim to contribute to a better understand how such zones may affect flow in geothermal fields of Mexico and basement petroleum reservoirs in the Norwegian Continental Shelf.

The effect of fluid pressure and composition on hydrothermal vein precipitation rate, permeability and microstructure

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Mineral veins in fossil geothermal systems are useful structures in determining the stress, strain, pressure and temperature that a rock mass has experienced, as well as fluid pathways and composition. Experimental studies to date suggest that fracture healing in rocks containing pore fluid is a function of time, temperature and fracture dimensions. Dependence on fluid pressure and fluid composition is less well constrained experimentally. This study aims to characterise the evolution of microstructure, permeability and precipitation rates during changes in fluid pressure for quartz or calcite solutions.

To help understand this evolution, a new high-pressure, high-temperature triaxial deformation apparatus at the University of Liverpool has been designed to simulate a range of upper crustal geothermal gradients. Effective pressures of up to ~100MPa can be controlled whilst simultaneously heating samples to ~750°C using an internal furnace. Static experiments are carried out by supersaturating low porosity, fractured isotropic samples with pore fluid containing minerals in solution, and dropping the fluid pressure at different rates after a set hold period. Evolution experiments, where similar pore fluids are flowed through the sample at different rates, were designed to investigate the effect of fluid flux on precipitation and permeability. Resultant microstructures can be compared to natural examples from an exhumed geothermal system, and considered in terms of vein growth mechanisms.
Data emerging from this new experimental setup can be applied to subsurface models of geothermal reservoir production or stimulation, by predicting the conditions under which precipitation is most likely to increase scaling in wells or reduce reservoir permeability.

Permeability reduction from porosity occlusion due to CO_2 - rock interaction: implications for carbon capture and storage.

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To ensure the effective long-term storage of CO_2 in potential geological storage sites, evaluation of leakage pathways and permeability changes due to fluid-rock interaction should be undertaken. Here we use a series of natural CO_2 seeps along a fault in South Africa to assess the controls on CO_2 leakage to the surface. Detailed mapping reveals extensive fracturing along the mapped fault trace. Measurements of gas flux and CO_2 concentration, at sites along the fracture corridor, give 27% CO_2 concentration (maximum soil gas measurements), and a flux of 191 g m^{-2} d^{-1}. Flux and concentration measurements, with observations of gas bubbles in streams and travertine cones attest to CO_2 migration to the surface. Permeability measurements on the host rock units show that tillite above the sandstone should act as an impermeable seal to upward CO_2 migration to the surface.

The combined permeability and fracture mapping data indicate that fracture permeability creates the likely pathway for CO_2 migration through the low permeability tillite. Heterogeneity in fracture connectivity and intensity at a range of scales creates local higher permeability pathways along the fracture corridor. However, analysis of thin sections reveals that porosity occlusion occurs through time due to fluid-rock interaction decreasing fracture permeability. The results have implications for the assessment and choice of geological CO_2 storage sites, particularly in the assessment of sub-seismic fracture networks and the interaction of CO_2 fluid with rocks on permeability.

Influence of salt tectonics on the subalpine chains of SE France; from Tethyan rifting through to Alpine compression

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Salt tectonics plays an important role on many passive margins world wide, including the South Atlantic Margin and the Gulf of Mexico. The advances in understanding in the last several decades have been largely driven by the exploration and seismic imaging of these margins. This increase in understanding has led to the reexamination of salt related deformation structures in outcrop within fold and thrust belts. The Subalpine Chains of SE France, for example, represent an ideal location for the development of salt related structures, due to the presence of Triassic evaporites and the areas location on the European plate margin during Early Jurassic Tethyan rifting and subsequent Middle Jurassic to Middle Cretaceous thermal subsidence. Despite this, the role of salt movement in the pre-Alpine tectonic evolution of the area has largely been ignored, although recognition of halokinetic deformation is complicated by overprinting of structures related to Alpine shortening.

Field mapping and section restoration was conducted along a major strike-slip fault zone between the towns of Rouaine and Daluis. This “Rouaine-Daluis Fault System” has undergone approximately 6.4 km of sinistral displacement since the Oligocene. When restored to pre-Oligocene conditions, Eocene to Oligocene limestones and marls were placed adjacent to a large body of Triassic gypsum. A model involving the syn-depositional extrusion of salt along the fault system is invoked to explain considerable thickness variations in the Eocene to Oligocene stratigraphy.

Additional stratigraphically out of place Triassic gypsum bodies were observed trending parallel to the Rouaine-Daluis Fault System, in direct contact with Jurassic to Middle Cretaceous units. Bedding relationships between this allochthonous Triassic gypsum and Aptian-Albian shales suggest that a salt wall trending parallel to the Rouaine-Daluis Fault System was exposed at the sea floor as a salt canopy during the Middle Cretaceous. Halokinesis has evidently been influential on the tectonic evolution of the Subalpine Chains since evaporite deposition in the Triassic, and the resulting salt structures were critically oriented for sinistral strike-slip faulting during Alpine shortening.

Controls on fault activation and slip along the Húsavík-Flatey transform fault, Northern Iceland

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In a range of geological settings, repeated slip occurs on faults that are misoriented with respect to regional principal stress orientations. Such faults must be weak relative to laboratory-derived rock strength. Here, we examine the Húsavík-Flatey fault (HFF), a NW-SE-striking dextral oceanic transform fault that forms the principal structure of the 120 km long Tjörnes Fracture Zone (TFZ), and emerges onshore in northern Iceland. The HFF is estimated to accommodate up to 60 km of strike-slip displacement and ~1.4 km of vertical displacement, placing Cenozoic extrusive volcanics in the footwall against Upper Pleistocene post-glacial sediments in the hanging wall of the fault. Stress inversions based on present day seismicity indicate a first-order maximum horizontal compressive stress (S_{Hmax}) orientation subparallel to the fault, and a second-order S_{Hmax} oriented approximately perpendicular to the fault. The high angle between the HFF and these stress vectors indicate that the fault is severly misoriented. Using exceptional coastal exposures of fault and fracture networks surrounding the HFF, we derive local paleostress histories, and examine the mechanisms that control deformation along this fault.

Mapping of a ~3.5 km long coastal transect, situated where the fault emerges onshore north of the town of Húsavík, reveals a diffuse and highly heterogeneous fault population that reflects a complex paleostress history. Deformation within 1.5 km of the HFF includes closely spaced, small-displacement faults. These faults are characterised by dilatation, indicated by well-developed fault breccias and pervasive networks of extension fractures, occurring as discrete sets of crack-seal, and intrafault veins. Between 2.5 and 3.5 km of the HFF, deformation is dominated by a smaller number of larger displacement normal, and dextral-normal faults. These faults are characterized by intensely foliated smectitic gouge, and crosscut limited early vein populations.

Paleostress reconstructions using fault and vein data, and cross-cutting relationships, indicate that approximately half of the mapped deformation was associated with stress states where S_{Hmax} is oriented either sub-parallel or sub-perpendicular to the transform, consistent with stress inversions based on the instrumental seismic record. Additional local stress states indicate a progressive reorientation of S_{Hmax} through time, but the relative timing of stress states and rotation of S_{Hmax} varies significantly between sites.

Mapped structures do not represent a uniform succession of well-oriented, partitioned slip events within the transform boundary, but reveal evidence for episodic slip on structures that should be misoriented for frictional reactivation in all of our derived paleostress states. Weakening mechanisms include local temporal fluctuations in fluid overpressures (proximal to the HFF core) and fluid-rock interaction leading to alteration of primary basalts to weak clays (distal from the HFF core), resulting in time-dependent and spatially variable rheological and frictional properties.

Casualties of War: Microstructural damage to stone heritage by ballistic impacts

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The built environment has been targeted during conflict for centuries. Contemporary conflicts have seen a resurgence in the ideologically-driven destruction of cultural heritage, such as the sacking of Mosul and Palmyra by ISIS/Daesh. The impact of ballistics on stone heritage is part of a wider spectrum of imposed damage that has serious implications for the structural integrity and strength of masonry. Microstructural studies and X-ray tomography have shown that even low calibre impacts can generate internal fracture networks far from the site of impact, leading to loss of subsurface density. Much like tectonic or meteoritic microstructures, our detailed analysis of ballistic impact structures give valuable insight into the mechanisms and conditions of deformation.

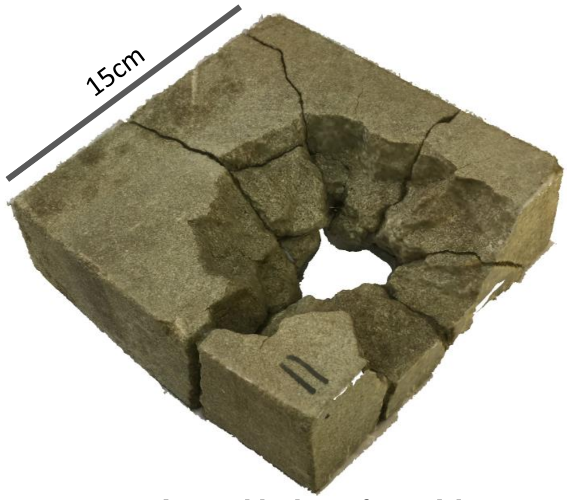

Figure 1: Sandstone block perforated by an AK-103 rifle round. Exit cavity is upward facing.

3D surface scanning and photogrammetry provide accurate 3D models of impact crater morphology and surface fractures, allowing for a correlation of visible damage to potential internal damage networks (Fig.1). Radial fractures originating from an impact site have fragmented a target into angular blocks (up to 10cm). The impact crater (~7.5cm diameter) and exit cavity (~10cm diameter) are significantly larger than the bullet diameter (7.92mm), but actual perforation tapers to ~2.5cm across. This is the result of material being ejected from the impact crater, like ejecta from a meteorite impact. The size of target fragments increases with distance from the impact site, suggesting a correlation between stress experienced and proximity to impact. It was possible to reconstruct large clasts near perfectly, but not ejecta material. Highly reflective fracture surfaces suggest planar fracture of quartz, mirroring observations from meteorite impacts. These microstructures suggest that ballistic impacts may form a low-pressure end member of shock microstructures.

Study of ballistic impacts can lead to novel insights into structural geology, as well as being beneficial for the conservation of built heritage. For example, fracture surface topography is useful for analysing the mechanics of dynamic fracture propagation, and how it may differ from static systems. Diagnostic features of dynamic fracture, such as planar quartz surfaces, can be described and compared to earthquake damage.

Formation of the West Siberia Basin: A new interpretation

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The West Siberia Basin is formerly regarded as a Mesozoic to Cenozoic post-rift sag basin on top of a Triassic rift basin. This interpretation is based on gravity and magnetic data, however 2D seismic data does not support a rifted origin. Triassic sediments appear to onlap basement topography without displaying growth strata. Post-Triassic strata appear to be isopachous and generally onlap basin margins with the exception of Neocomian clinoforms. Instead, gravity and magnetic anomalies observed in the basin are probably related to the heterogeneity of the basement.

In order to examine the formation mechanism of the basin, a 2-D lithospheric forward model based on the generic model by McKenzie and Priestley (2016) is constructed. The model suggests subsidence of intracontinental sag basin is caused by increasing temperature in the lithospheric mantle during preceding orogen and subsequently cooled by post-orogenic erosion.

The West Siberia basin is preceded by the Devonian-Carboniferous Uralian orogen and we consider the orogen had a similar areal extent as the basin. Our model shows the thickened orogenic crust formed a thick low conductivity layer that restricted the dissipation of heat from the Earth's mantle. It caused an increase in temperature at the base of the crust during the late Carboniferous and Permian. The temperature peaked during Permo-Triassic transition and coincides with the Siberian traps magmatic event. During the late Permian and early Triassic, rapid erosion associated with the active uplift of the Siberian traps thinned the crust to its present-day thickness. By reducing the thickness of the less conductive crust, it allowed effective thermal cooling of the heated lithospheric mantle and caused continuous thermal subsidence of the basin from the middle Jurassic until early Miocene. We believed the timing of the erosion correlates with the deposition of thick Permo-Triassic sediments in the South Barents Sea basin and its Uralian provenance based on seismic data.

The subsidence curve produced by the model is in accordance with the sediment-loaded subsidence curve produced from 2-D flexural backstripping. Based on our sensitivity testing, we suggest the main controlling factor for subsidence in this model is the amount of erosion, given that the lithosphere has sufficient amount of time to heat up (~20Ma). We believe the model can explain the subsidence pattern of the West Siberia Basin and is consistent with the occurrence of Uralian orogen and Siberian traps.

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Permeability reduction by cataclastic deformation bands in mixed aeolian-fluvial facies reservoirs

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Deformation bands are a type of strain localisation structure associated with faulting and folding of porous sandstones, that modify the microstructural and petrophysical properties of hydrocarbon bearing reservoirs. Current understanding of deformation bands is drawn largely from observations in aeolian systems, where they have been shown to reduce permeability on average between two to four orders of magnitude. It is understood that they form preferentially within the higher porosity and coarser grain size units within these systems, and therefore they may act to homogenise the reservoir in terms of permeability and fluid flow pathways[1]. Little attention has been given to bands hosted in successions with a mixed aeolian-fluvial origin, which exhibit a broader range of lithologies, with a larger range of textural and petrophysical properties. Therefore, a suite of deformation bands obtained from a variety of lithofacies within the Sherwood Sandstone Group (SSG) of the UK, are examined with respect to their microstructural and petrophysical properties. Lithofacies are grouped into deformation band lithotypes classified by these properties in order to assess reservoir potential, band susceptibility and subsequently the impact on fluid flow.

Bands are identified in lithofacies once thought unfavourable for band formation, including in those expected from observations in aeolian studies. Bands are identified in five of our six lithotypes, thus identifying a potential grain size and porosity limit to band formation of 130 µm and 5% respectfully. Petrographic analysis of both host rock and deformation bands show much lower porosity and thus lower permeability reduction than previously recorded, with reductions of between three and eight orders of magnitude, with significant variability between deformation band lithotypes. By combining these permeability contrasts with harmonic averaging in a simple injector-producer reservoir schematic[2], their impact on fluid flow is quantified. Results show how preferential reservoir host rocks are most severely affected by deformation band formation, and become the major baffle/barrier in the system, whilst poorer quality hosts, while still affected by band formation, become the major fluid flow pathway.

These results show that deformation band prediction in mixed aeolian-fluvial systems, whilst complex, is possible through identification of susceptible lithotypes. The potential impact of these structures on reservoir quality is also much greater than previously recorded, and in complex systems, may maintain or further enhance reservoir heterogeneity.

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The effects of salt tectonics in the evolution of a fold and thrust belt, Southern Subalpine Chains, France

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Many of the fold and thrust belts in the Alpine domain (e.g. Betics, Rif, Carpathians and the Alps) comprise evaporitic successions. The structural style and evolution of these orogens has been affected by salt tectonics. The Southern Subalpine Chains of SE France is one of these mountain belts, and it contains a well-documented succession of Upper Triassic (Keuper) rocks that include gypsiferous evaporite bodies associated with many of the Alpine structures.

The Southern Subalpine Chains formed the passive margin of the Alpine Tethys during its Jurassic-Cretaceous rifting and thermal subsidence phase. During the subsequent Alpine shortening the incompetent evaporites and variegated gypsiferous shales have had a significant impact on the development of the fold and thrust belt, but the role of the salt-related structures in the preceding passive margin phase is largely unclear. This mountain belt provides an outstanding natural laboratory for the investigation of the salt-related deformation including those developed before the fold and thrust belt formed.

Detailed geological mapping and section construction was carried out in the vicinity of Castellane. The central Chasteuil dipair is bounded by kilometre scale minibasins containing Triassic to Tertiary aged rocks. Incomplete, condensed and overturned Jurassic sections adjacent to the diapir represent the elevated roof of the diapir and an overturned megaflap indicates salt extrusion at the seafloor. Unconformities, stratal and structural geometries suggest that the diapir and adjacent salt-walls grew from the Early Jurassic (Hettangian) to the Early Cretaceous (Valanginian). The structures have subsequently been tightened and further deformed by Alpine shortening from Late Cretaceous to recent times.

Salt tectonics identified through accurate mapping and cross-section construction shows that there was a significant pre-Alpine deformation throughout Late Jurassic-Early Cretaceous times on the European Tethyan passive margin. The structural evolution of the passive margin was effected by salt-tectonics during the syn-rift and post-rift stages of Alpine Tethys. Subsequent Alpine shortening has affected an already deformed succession and modified the older halokinetic structures. The original geometry of salt related structures have had effects on the structural style of the evolving thrust faults. The hinterland dipping limbs of the salt walls/pedestals served as ramps and determined the paths of Alpine thrust faults.

Does cleavage matter?
Investigating the influence of cleavage planes during granular flow

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Fault gouges are amongst the main products of strain accommodation in the brittle upper crust. During shear, fracturing has a direct effect on grain size (and shape) evolution and ultimately grain-grain interactions. Such changes are likely to influence how stress is accomodated within the gouge and, on a broader scale, the mechanical and petrophysical properties of faults. Most microphysical models for the deformation of granular materials assume particles have isotropic properties. However, natural fault zones are often composed of minerals (e.g., carbonates, phyllosilicates, feldspars and amphiboles) that have well-defined crystallographic anisotropies, such as cleavage planes, twin planes, and healed fractures. Recent observations of both natural and experimental strain localisation features have highlighted the potential for crystallgraphic anisotropy (such as cleavage planes) to play a key role in control fracturing processes (e.g., Cavailhes and Rotevatn, 2018, *J. Struct. Geol.*). As a result, the occurrence of such anisotropies in natural gouges may strongly influence the rheology of a fault during deformation.

Numerical simulations using the discrete element method (DEM) approach have proved, in recent years, to be a powerful tool in revealing grain scale processes associated with frictional sliding of granular fault gouges. Such an approach affords us unusual access inside a deforming fault zone to track precisely which grain process are active and how they interact. We can also directly view their influence on macroscopic sliding. Additionally, such a method now allows us to build geomaterials with specific structural and mechanical properties and the ability to tune or even switch on and off certain features to elucidate their influence. Though technically possible experimentally, such an investigation would require exensive suites of serial experiments stopped at increasing strains which is not only extremely time intensive but is often hampered by inherent variability in natural samples.

In this contribution, we will summarise recent experimental work linking crystallgraphic anisotropy to preferential grain fracture and present preliminary results on the numerical investigation of how weak cleavage planes affect grain fracture of sheared granular materials. A better understanding of the role of mineral anisotropies on fault mechanics will improve the development of more accurate microphysical models for gouge friction evolution during faulting.

Seismic forward modelling of carbonate hosted normal faults

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Carbonates are prominent reservoir rocks around the world, and account for 50-60% of all oil and gas reservoirs. In many carbonate hydrocarbon plays worldwide (e.g. in the Barents Sea, Norway), seal- and retention failure is recognized as a major risk factor. Whereas the understanding of fault properties and imaging has improved in siliciclastic reservoirs, less is known for carbonate faults. This motivates investigation into carbonate fault zones as well as their properties and imaging in the subsurface.

To do this, we use seismic forward modelling to elucidate the relationship between fault geometry, throw, petrophysical/geophysical properties and seismic fault imaging; the forward models are based on carbonate-hosted fault zones at various scales from outcrops. Although the overall project scope is to investigate faults with throws ranging from >1m to 5 km, we here present a part of the project that focuses on seismic forward modelling of faults with throws that are approximately equal to, or below, vertical seismic resolution, to investigate how relatively small scale (c. 1-15 m throw) faults manifests in (or affects) the imaging of a faulted carbonate succession. The seismic forward models are based on faults affecting a limestone succession in Malta, and preliminary results will be presented. This study may help improve the understanding of the relationship between seismic images of faults and the geometry and properties of those faults. This in turn may help reduce the exploration risk associated with carbonate plays in hydrocarbon basins globally.

Failure mechanisms in travertine and the impact on acoustic properties

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Understanding continental carbonate deposits is of increasing importance due to their great hydrocarbon reservoir potential, particularly with the development of lacustrine carbonate plays within the 'pre-salt' of the South Atlantic, for example in the Santos and Campos Basins, offshore Brazil. These deposits, however, possess significant heterogeneities related to complex chemical and biological depositional and diagenetic processes, which influence the petrophysical properties and seismic anisotropy of these rocks. In comparison to established concepts of faults within clastic rocks, the heterogeneous nature of carbonates means that faulting within these deposits is also difficult to model and predict. Understanding the failure mechanisms within these rocks is therefore imperative to understanding faults in these settings. This integrated petrophysical and geotechnical study characterises the heterogeneities associated with the Tivoli Lapis Tiburtinus travertine located in the Acque Albule Basin in Italy with the aim of understanding the control these heterogeneities have on failure mechanisms and the resulting changes in acoustic and seismic properties.

The Lapis Tiburtinus travertines, formed as a result of calcareous precipitation from hydrothermal fluids fed by a N-S striking strike-slip fault. They are composed of a number of different facies types, which have distinct petrophysical properties. Changes in facies are observed over millimetre to metre scales and is dependent on the depositional setting (i.e. hydrodynamic setting, surface topography, microbial community etc.). Common travertine facies observed in Tivoli include dendritic shrub and coated gas bubble layers which typically have significant porosity of up to ~30% (average porosity ~10-15%) interbedded with low porosity layers such as dense micrite crusts which lack observable macro-porosity. Differences in rock characteristics across these facies results in a highly anisotropic, heterogeneous rock where permeability changes (measured with a probe permeameter) up to three orders of magnitude are observed to occur over centimetre scales. The different layers of these travertines therefore have widely varying mechanical properties, which will influence the failure mechanisms in these rocks. Triaxial testing of several travertine core plugs was conducted at a range of confining pressures whilst simultaneously measuring the sonic velocity. As the travertine samples are composed of >95% calcite, grain density is largely consistent so the variable seismic anisotropy and response during failure can be related to other parameters such as porosity, porosity type, texture and fabric of the sample. Sonic velocity analysis allowed characterisation of heterogeneities within samples, where relationships between a number of parameters and seismic anisotropy were recognised. These results coupled with mechanical analysis during failure further allowed the changes (if any) in acoustic properties to be quantified in relation to failure.

The combination of triaxial and acoustic testing brings about an enhanced understanding of the control of facies type upon failure mechanisms, faulting styles and, ultimately, acoustic properties in travertines. The mechanical properties of travertines are largely dependent on the dominant facies type, which we show to influence faulting and the seismic anisotropy of the rock. This characterisation of sonic velocities of both fractured and un-deformed travertine samples could be applied to recognising fractured and faulted travertine deposits in geophysical data such as acoustic logs and seismic images.

A combined modelling approach to plate vector rotation in rift-transform intersections.

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Transform margins are first-order structural features that represent a total of 16% of the cumulative length of continental margins accommodating plate motion. Yet, their evolution, genetic relation to oceanic spreading, and general structural character still present a challenging research field. In this work, we investigate the evolution of rift-transform intersections using a combined analogue and numerical modelling approach.

Through a series of analogue experiments, we investigate the effect of an imposed rotation in the rift extension direction, a component in rift-transform interaction that has not been studied previously. In the model, we use a two layer ductile-brittle configuration to simulate the crustal rheology. We initiate rifting in an orthogonal direction and then proceed to gradually rotate the plate vector to a seven degree angle. This angle is comparable to the amount of rotation seen in natural examples. Rifting then continues with the new plate motion vector. The experimental configuration we use allows the study of transpressional and transtensional rotation of the moving plate simultaneously. Preliminary results show that: a) a transtensional shift in the plate direction produces en-echelon oblique slip faults (alongside a principal displacement zone) which accommodate the horizontal displacement until the new plate motion vector is stabilized and b) a transpressional shift produces buckle folding near the rift-transform intersection and widespread transpression further away from the rift. Using the open source geodynamics code ASPECT, we present a suite of 3D numerical models of lithospheric rifting in the presence of plate vector rotation. Our numerical simulations complement the analogue models while exploring the rheological and mechanical parameter space that guides our preliminary results.

Finally, we then compare our observations from the combined modelling approach with seismic reflection images from a range of margins around the world, including the Gulf of California partitioned oblique margin and the Davie Fracture Zone in the West Somali Basin.

Using Variscan Metasediments as an EGS Reservoir on a European Scale – Preliminary Stages of Outcrop Analogue Characterisation.

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The MEET (Multidisciplinary and multi-context demonstration of Enhanced Geothermal Systems exploration and Exploitation Techniques and potentials) aims to explore and bring about the potential in Variscan crystalline and metasedimentary reservoirs. This project will focus on the conversion of the University of Göttingen's natural gas power plant, into a geothermal power plant to supply the district heating, focusing on the structural model of the reservoir.

Through investigative surveys, the target horizon has been identified as Variscan metasediments (meta-greywackes, slates and quartzites) contained in the Variscan fold and thrust belt, which has been locally overprinted by younger tectonics related to the Leinetal Graben system. Suitable outcrop analogues can be found from the Rhenish Massif in the Harz Mountains. Through intensive field campaigns and photogrammetry sessions the potential reservoir rocks will be characterised to eventually create a 3D structural model of the reservoir beneath the Göttingen campus. From this structural model, general conceptual reservoir models will be created.

The preliminary research presented shows the first stages of the characterisation of one of the chosen outcrop areas located in the Western Harz and the planned future workflow for the building of the structural model. Due to the complexity of the deformation, a heavy focus has been put on the fold and thrust structures and how these affect fracture network characteristics such as density and topology. This includes the initial structural field data and preliminary interpretations of the fold structures of the outcrop through digital methods. Throughout this presented work, I aim to address the next steps in creating a detailed structural model of the Variscan metasediments as seen in the Harz Mountains.

Extension initiation and localization on minibasin formation in passive margin salt basins

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Passive margin salt basins are typically characterized by an extensional domain in upslope regions. While many studies have focused on salt-related extensional structures, only a few studies have focused on the influences of thin-skinned extension on minibasin formation. Using scaled analogue experiments integrated with a high resolution strain analysis method (digital image correlation, DIC), we study the evolution of extensional structures during thin-skinned extension. The results show that extension related diapirism and minibasin development undergoes three stages. In the first stage, widely distributed, rather diffuse extension occurred in a large area of the upslope region. In the second stage, many small, 2-8 cm long normal faults and extensional grabens initiated as extension gradually localized onto them. In the final stage, as the supra-salt cover strata thickened due to syn-sedimentation, some of these extensional structures became buried and inactive and only the largest structures continued to grow, leading to thin-skinned, reactive diapirism. As a result, in the area between some diapirs, minibasins occurred over abandon and buried normal faults and extensional grabens. Similar abandoned normal fault systems beneath minibasins can be observed in high quality 3-D seismic reflection data from the Lower Congo Basin. These normal faults have Cenomanian to Turonian in age and are 5-10 km long with 1-4 km spacing and up to 150 ms TWT maximum fault throw. Later extension mostly localizes onto salt diapirs where the strata onlap onto the salt. This study shows that extensional diapirs and minibasins in between may result from gradual strain localization during thin-skinned extension. Consequently, minibasins superimpose on regions with early complex fault systems related to extension. This process of minibasin growth is an addition to current models of extensional minibasin formation and suggests a fracture system may be well developed for hydrocarbon migration and storage, within the lower most strata of an intact minibasin.

Controls on normal fault activity in the central Italian Apennines: Insights from thermo-mechanical modelling

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In the seismically active central part of the Italian Apennines, extensional faulting and devastating earthquakes occur within a narrow (<100 km wide) zone along the crest of the mountain range. While the underlying mechanism is still highly debated, strong evidence exists that enhanced elevations in this central area cannot be explained by thicker crust compared to adjacent parts of the Apennines. Instead active surface uplift and extensional faulting in this area over the last ca. 3 Myr appears to be related to the removal of mantle lithosphere. In particular, the width of the zone of extension and spatial and temporal variations in extensional strain rates appear to correlate systematically with the distribution of topographic elevation.

We investigate factors controlling the evolution of faulting and topographic development in response to the removal of mantle lithosphere using a 2D thermomechanical model. Surface uplift in our model is generated dynamically by the progressive convective removal of dense mantle lithosphere (triggered by a small thermal anomaly) and replacement by hot less dense sub-lithospheric mantle leading to isostatic uplift. Faults (predefined weak fault zones), in turn, respond dynamically to both topographic uplift (gravitational effect) and rheological changes.

In general, our model demonstrates the large impact of mantle dynamics on both topographic development and normal fault activity, confirming previous work. More specifically, we observe in the model changes in the spatial pattern of fault slip rates over time and in the degree of strain localisation. We evaluate over what time scales these different developments occur and what the relative contributions are of faulting and regional uplift for topographic development. Overall, we constrain our model and evaluate our results using observational data from the central Apennines.

Lithon morphology and change in carbonate elastic properties in a regional fault zone

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Dolomitized carbonates affected by the Neogene Carboneras fault zone (southern Spain) are qualitatively and quantitatively described. Despite their complex tectonic history, two main groups of structural features can be recognised: (1) Features prior to strike-slip faulting, here deformation was accommodated by a network of sub-vertical mode I fractures and bedding-parallel stylolites. (2) Features resulting from overprinting within the fault zone, consisting of a fracture system associated with the carbonate damage zone and fault core.

We analyzed the morphology of the deformed dolostone clasts ('lithons'), which characterize the structural fabric within the fault zone. Lithons occur frequently in the breccia zone and are texturally-distinct. The lithons in the breccia zone include fragment of wall-rock commonly containing broken stylolites, veins, and various fault damage products. Orthorhombic rock lithons, a few cm in dimension, are generated from the intersection of fracture sets with bedding and/or joints. Fractures intersect at approximately 90 +/- 20^{o} and dip from steeply inclined to vertical. Four main fracture sets were recognised: NNE – SSW (set 1), NW – SE (set 2), WNW – ESE (set 3) and N – S (set 4). The dominant NNE – SSW (set 1) and a NW – SE (set 2) striking fracture groups formed conjugate pairs. The results of the computed spacing of the dominant fracture sets 1 and the calculated coefficient of variation (*Cv*) suggest that the lithons are well clustered. In addition, the cross-sectional aspect ratio of lithons have an average value of 1.6 and standard deviation of 1.5. Lithons dimensions below 1cm and above 2cm represent about 10.5% and 9.5% of the total measured lithons respectively, whereas 48% of the measured lithon dimension correspond to the range of 1 – 1.6cm. We argued that the lithon's aspect ratio are statistical identical, irrespective of their dimensions. Lithon size and morphology changes laterally across the fault core. The lithon's morphology change and cluster contribute to the overall permeability of the carbonate rock. We compared the changes in elastic properties in relatively undeformed and intensely deformed dolostones.

Multiphase rifting controlled by pre-existing basement structures: A case study of the Utsira High, South Viking Graben, North Sea Rift, offshore Norway.

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The propensity for pre-existing intra-basement structures to perturb and re-orient the stress field during later tectonic phases has received increased focus in recent years. Understanding how the 3D geometry of basement heterogeneities influence subsequent multiphase rift faulting on a regional and fault array scale is difficult in outcrop, and subsurface characterisation of deep basement structures may often be hampered by inadequate seismic imaging. The relationship between pre-existing basement structures and rift-related structures, especially their 3D geometry and interaction, has therefore not been extensively documented.

In this study we combine both regional 2D and 3D seismic reflection data, covering the Utsira High and surrounding areas, to investigate the 3D geometry of intra-basement structures and analyse how they perturbed the stress field during later rift episodes. Our study illustrates a sequential deformation history where pre-existing extensional shear zones related to the collapse of the Caledonian orogen subsequently influenced the Permian – Triassic and Upper Jurassic – Lower Cretaceous rift episodes. We show how the extensional shear zones locally perturbed the stress field, manifested by rift faults that trend oblique relative to the general E-W oriented stress field during deformation. Moreover, we show how the pre-rift geometry of the extensional shear zones (curved in map view and anticlinal) promotes crosscutting or merging interactions with the rift faults, with rift axis migration from the east to the west of Utsira High between the two rift episodes. Also, we illustrate how the 3D geometry of the pre-existing extensional shear zones locally facilitated strain localization and thus influenced the along strike structural variability of the South Viking Graben.

Our study shows that the 3D geometry of the extensional shear zones had direct implications for both fault array and regional scale distribution and geometry of Permian-Triassic and Upper Jurassic-Early Cretaceous structures in the study area. Furthermore, our result has broader implications for understanding trap formation, reservoir distribution, and fluid migration pathways in an area with active hydrocarbon exploration and production.

How lithology, tectonic setting, and fault size control normal fault growth: Using a large global database to find trends in fault kinematics

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Knowing how normal faults grow provides the basis of our understanding of rift basin development, and the distribution and size of potentially hazardous earthquakes. The growth of normal faults is commonly described by two main 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. Recently, a third, hybrid model has been suggested, where faults follow the propagating fault model for ~20-30% of their lives, and the constant-length model for ~70-80%. This poster critically examines these competing models by compiling D vs. L vs. time/strain data from >100 published outcrop, seismic reflection and physical modelling studies for which the partitioning of D and L are well-constrained. The first fundemental question we aim to answer is, what is the timing of displacement vs. lengthening stages of fault growth, and percentage of a fault's life is spent lengthening vs. time spent slipping and accummulating displacement? The second question we aim to answer is, how do factors such as lithology, pre-existing faulting, regional strain, and fault size affect normal fault growth? Previous studies have suggested that pre-existing faults or 'strong' barriers to rupture may cause faults to lengthen and be under-displaced. To answer these questions, we create a database of fault length, displacement, and timing, along with lithology, tectonic setting, and a range of other factors; this database will be open-access, available for analysis and manipulation by the broader structural geology community, and frequently updated. To the best of our knowledge, this is the first attempt at such a comprehensive, integrated study of this style and of the factors influencing the growth of normal faults.

Using U-Pb calcite geochronology to constrain the timing of fracturing and fluid-flow in Jurassic mudrocks of the Cleveland Basin

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Organic-rich mudrocks are of great significance to the petroleum industry, potentially acting as top seals, source rocks and/or unconventional reservoirs. Natural fractures within mudrocks can strongly influence top seal integrity, primary migration and the performance of unconventional (e.g. shale gas) reservoirs. This PhD project combines structural geology with isotope geochemistry and novel U-Pb calcite geochronology to constrain the relative and absolute ages of faults and fractures within an exhumed, early mature, Early Jurassic mudrock succession in the Cleveland Basin, NE England. The abundance of well-exposed, natural fractures with different orientations and failure modes provides an opportunity to investigate the properties of these fractures and how they relate to palaeo-fluid flow. This project will develop an integrated understanding of fracture initiation and reactivation and fluid migration history during burial and exhumation of the Cleveland Basin.

The Cleveland Basin is an extensional basin that formed in the Mesozoic and overlies earlier, Carboniferous and Zechstein (Permian) depocentres. Both the northern and southern margins of the basin are highly faulted with the northern margin dominated by N-S/NNW-SSE striking normal faults. The southern margin is characterised by the E-W striking Flamborough and Vale of Pickering Fault Zones which have undergone both normal and strike-slip motion.

Multiple crack-seal-slip calcite fault fills (some of which contain bitumen) from a selection of minor (<2 m offset) to major (Peak Fault) N-S faults have been sampled and analysed for an initial pilot study. Most faults sampled have a normal, dip-slip sense of movement with no observed indications of reverse reactivation. These mean the calcite U-Pb dates can be used as an indicator of the timing of fault slip. The methodological approach involves the combination of optical and SEM-based imagery, elemental mapping with isotopic data; the aim being to link obtained U-Pb dates to specfic fault-slip events.

Our initial study comprises nine successful dates, all ranging from 36 to 27 Ma (latest Eocene to early Oligocene), with pooled mean ages of 32 Ma (Staithes to Runswick Bay) and 29 Ma (Peak Fault, Ravenscar). These ages are significantly younger than the previously interpreted Jurassic to latest Cretaceous normal fault movements, and document an unrecognised period of Cenozoic extension in the Cleveland Basin, which we link to salt tectonics, evidence for which is preserved offshore in blocks 42/29 and 47/4b. This event could have a previously unrecognized control on the migration of hydrocarbons within the Cleveland Basin and possibly the Southern North Sea. More fundamentally, the presence of bitumen in calcite-filled faults with Cenozoic ages raises important questions concerning the mechanism and timing of maturation and uplift within the Cleveland Basin. This project will focus on detailed analyses of the timing and process of fracture initiation and propagation in mud-rich lithologies, and demonstrate the applicability of U-Pb calcite geochronology to understanding local and basin-scale tectonics.

Review of proposed Ord Window structures: thinking in three dimensions

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The Moine Thrust Zone (MTZ), running NE-SW for 190 km along the west coast of Scotland, has been studied for centuries. Many of the structures along its length, though complex, are well understood and are regularly used in textbook case studies. A marine Cambrian – Ordovician sequence forms the upper autochthon which can be seen along the length of the thrust zone through windows in the overlying nappes e.g. the Assynt Window. However, these structures are poorly understood at the south-western end of the exposed MTZ where the Cambrian – Ordovician sequence outcrop in the Ord Window, of Skye. The Ord Window offers a view to the highly deformed sub-nappe lithologies and an excellent opportunity for field study of these intricate structures. Much of the outcrop stratigraphy at Ord appear entirely overturned due to thrusting and subsequent folding. Dispute over the relationships of these structures have resulted in many published models, depicting quite different interpretations. Here I apply structural field data to constrain these models and present a model for cross-cutting thrust propagation. The work presented integrates existing regional cross section models with detailed three-dimensional interpretations derived from field data. The nature of the multifaceted structural evolution of the Ord Window area lends its self to rather open interpretation but integration of regional cross sections with field data and 3D model building constrains some of the ambiguities of current models. Large scale thrust systems can be found all over the world but most do not allow direct study of deformation within the footwall units. This means that well exposed, easy to access sites like Ord should be studied and modelled to the highest possible quality in an aid to understand less or unexposed field areas.

Damage scaling and fault segmentation in carbonate rocks

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Fault damage zone presents a renewal of interest to better understand stress perturbation around faults, earthquake's ground motions and fluid flow in the upper crust. Although numerous studies provide significant amount of data from a broad variety of rocks, the processes controlling fault damage development are not clearly understood and their scaling properties in carbonate rocks remain poorly studied. *D-T* (displacement – damage thickness) data compilations show strong scattering and are acquired using different methods and at different places around the faults (including tip, wall, link, or inner and outer damages), therefore rendering difficult to define properly the scaling relationship.

In this study, we focus on the *D-T* scaling of faults only in carbonate rocks, and where measures along scanlines can be acquired far from the observed fault segment tips. This allows to focus on wall and/or link damages, and to avoid tip damage (i.e. process zone, extensive or compressive quadrant deformation) where the damage thickness can be very large compared to displacement. Scanlines of mode I fracture frequency (P10) were performed along 12 selected fault outcrops in France (Languedoc) and Spain (Maestrat Basin). The outcrops selected for the scanlines are large enough to reach the background fracturing, which was also characterized using map scale fracture analysis. We determine the damage zone thickness perpendicular to the fault plane and its error with a same methodology using the main trends in cumulative frequency diagram. Fault displacement (normal, reverse or strike-slip) and error bars have been derived from field data, using observed offsets of layers (outcrops and aerial images), layer dips, and slickenlines orientations.

The scanlines obtained from field data show logarithmic decrease of fracture frequency, with local frequency modes in the damage zone corresponding to secondary fault segments. This is consistent with outcrop and map scale observations revealing that the faults are formed of linked segments and abandoned tips in the fault damage zones thickness. *D-T* data comprised between 0 and 100 m fault displacement show a nearly linear *D-T* scaling (power law with exponent of 0.95, with a least square coefficient $R^2 = 0.97$). Including two additional data for $D > 100$ m, the best fit is a power law with an exponent close to 0.8 and $R^2 = 0.92$. As suggested by previous studies on fault damage zones, these data shows that damage thickness tends to saturate with increasing displacement larger than 100 m. These new data are thoroughly analysed with respect to fault segmentation observed in the field, and the linear scaling is explained by well-known processes of fault growth such as stress perturbation around fault and fault segment linkage.

Percolating force chains and propagating fractures in sandstone

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We investigate the impact of porosity on macroscopic strength in simulations of synthetic porous rocks with interlocking, breakable grains that match the grain structure of natural sandstones. These numerical experiments produce asymptotic relationships of porosity and uniaxial failure strength, consistent with experimental results. This previously observed and now numerically-reproduced relationship between porosity and failure strength arises from the spatiotemporal distribution of percolating force chains and propagating fractures. In sandstones, micromechanical models of failure concentrate on the relative importance of fracture development within grains or between grains. However, previous experiments and numerical models have not been able to compare these evolving microscopic contributions to macroscopic failure *in situ* under triaxial compression.

Our contribution reveals how porosity and confining stress control the spatial distribution and connectedness of system-spanning force chains as the rocks approach failure. Higher porosity and lower confining stress tend to localize the spatial distribution of system-spanning force chains. The amount of external work applied to the system closely controls the magnitude and rate of fracture development that occurs within these porous granular rocks preceding failure. The rate of fracture development relative to external work is approximately constant preceding failure for 2-20% porosity rocks, and that rate is higher in higher porosity rocks. For the same input of macroscopic energy, more fractures form in higher porosity rocks than lower porosity rocks preceding failure. When the strengths of the grains and cement are similar, brittle failure concentrates primarily within grains, rather than between grains, suggesting the dominance of Hertzian fractures. However, when the cement strength is lower than the grain strength, fractures develop with greater frequencies within the cement between grains, suggesting the importance of pore-emanated fractures. These rich numerical observations provide insights into the varying applicability of the pore-emanated and Hertzian fracture models, and the spatiotemporal distribution of load-bearing, system-spanning forces in rocks of varying porosity and internal strength distributions.

Fault Reactivation in the Southern North Falkland Basin: Complex Tectonic History or Partitioned Transtension?

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Typical problems when interpreting rifting histories include determining whether the rift system evolved under an extensional or transtensional stress regime, as well as the added complexity of reactivation of inherited basement structures and multiple rifting phases with different stress directions. Added to this are complexities regarding basin inversion, timing of inversion and compressional orientations. These can lead to misinterpretation of timings, stress orientations and relationships between structural elements. Further uncertainty arises from the range of possible interpretations when dealing with incomplete data sets, such as partial 3D and 2D seismic coverage and sparse wells. Regional geological interpretations of the Mesozoic North Falkland Basin (NFB) encounter all of the above problems. The NFB is composed of several sedimentary basins in the northern Falkland Plateau. The Falkland Plateau has experienced a long and complex geological evolution, which partially accounts for the range of complex structures observed in the NFB. The NFB is comprised of a series of offset depo-centres that are affected by two dominant structural trends: north-south oriented faulting in the Central and Northern NFB, whereas north-west to south-east oriented faults dominate the southern NFB. The main phase of rifting is likely to have initiated in the very latest Jurassic or early Cretaceous, with the NFB forming as a failed-rift arm associated with the opening of the South Atlantic. This rifting phase was then followed by a subsequent thermal sag phase that began in the Berriasian-Valanginian and continued under predominantly continental-lacustrine deposition until Albian-Cenomanian times, when the basin became increasingly marine in nature. Previous authors have suggested that a widespread Albian unconformity could be associated with regional uplift and inversion. A number of earlier studies have presented different evolutionary models for the NFB, but none seem to fully satisfy all of the observed structures. This contribution provides an alternative model for the structural evolution of NFB and accounts for inversion events in the SNFB and Central NFB without invoking a regional compressional event. By resolving stress orientations using fault slip analysis we demonstrate that structures interpreted as a result of successive phases of extension and compression, can instead be attributed to a single protracted phase of partitioned sinistral transtension.

The 1908 Mw 7.1 Messina Earthquake Italy revealed: 5m rupture of an offshore 70^o east-dipping normal fault

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To constrain the geometry and kinematics of the 28th December 1908 Messina earthquake (Mw 7.1), Italy, we use elastic half space modelling to replicate levelling data from 1907 – 1909, and the geology and geomorphology characterizing the Messina Strait. The earthquake caused >80,000 deaths and transformed earthquake science by triggering the study of earthquake environmental effects worldwide, yet its source is still a matter of debate. Modelling of the levelling data reveals slip along a well-known offshore fault, with a dip to the east of 70^o and 5 m dip-slip at depth, with slip propagating to the surface. It is remarkable that, even though these levelling data have been previously used in the last few decades, in this paper for the first time, a known active normal fault is used for elastic half space modelling to reveal the source of this paradigm-shifting earthquake. Furthermore, the associated co-seismic ground deformation is typical of other large normal faulting earthquakes, producing a clear geological and geomorphic expression. Geological and geomorphological observations that support maps of capable faults should not be ignored when attempting to identify the sources of major earthquakes.

Single Grain Orientation Analysis on Dauphiné twins in vein-quartz in slates (Ardennes, Eifel)

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Based on EBSD crystal orientation maps, single grain orientation analysis (SGOA) has been developed to distinguish between quartz grains free of Dauphiné twin boundaries (DTBs) and quarz grains containing DTBs (Minor et al. 2018). Using DTB-free grains in a series of experimentally stressed samples of a low-grade metamorphic quartzite, the SGOA revealed a particular relationship between the experimental compressive stress direction and the rhomb orientation distribution, showing the potential of the SGOA in the reconstruction of a paleostress state in naturally stressed quartz-bearing rocks.

Samples of a series of different types of vein-quartz (bedding-parallel, bedding-perpendicular and other fold and fault related veins) in slates from the Ardennes (Belgium) and Eifel (Germany) were used. Previous studies indicated that low-stresses (<50 MPa) are sufficient to induce Dauphiné twinning in quartz. In our samples, no post-kinematic deformation features were obversed, therefore we assume that DTBs were formed synkinematically during the precipitation of vein-quartz.

We apply the SGOA to assess individual quartz veins, analyzing and comparing the crystallographic orientation distributions, especially the r- and z-rhomb distributions, the bedding-perpendicular, bedding-parallel and other vein-arrays. We distinguish between grains free of Dauphiné twin boundaries (DTBs) and those containing DTBs. For DTB-free grains, the bedding-perpendicular veins are different to the c-axis orientation distributions, which are observed. The r- and respectively z-rhomb orientations distributions are mostly similar. The r-rhomb pole figures show a strong maximum around the center with a peripheral girdle distribution. Some samples are even approaching a single crystal, with a strong r- maximum around the center and two submaxima at 90 degrees to it. Bedding-parallel veins also show a variation in the c-axis distribution but the r-rhombs still show a strong maximum around the center and two submaxima. The samples from other vein arrays show a more complicated distribution of the c-axes, r- and z-rhombs orientations. We see one to two c-axis maxima, but only three r-rhombs. The DTB-containing grains were analyzed separately for both domains and compared with each other, and DTB-free grains were used as a reference.

In a future step, the relationship between the Dauphiné twinning related rhomb orientation distributions and the possible regional 3D-paleostress direction is to be deduced (e.g. Chen et al. 2016). Thus, the SGOA could be applied as a tool to use Dauphiné twins in quartz as an paleostress indicator.

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Cenozoic kinematics of the seismically active western continental margin of the Indian plate

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The Cenozoic deformation history along two adjacent brittle tectonic settings – E-W trending Kachchh rift basin and SW tilted, uplifted Saurashtra horst at the western continental margin of the Indian plate, located in the state of Gujarat, India, has been controlled by periodic reactivation of NW-SE, NE-SW and E-W trending, 0.25–50 km long oblique-slip and dip-slip faults.

The study is an attempt to establish the kinematic framework along sub-parallel, NW-SE striking group of intra-uplift, striated, high-angle faults, consisting of Vigodi Fault (VF) and its bifurcations – West Vigodi Fault (WVF), Gugriana Fault (GF) and its bifurcations – Khirasra fault (KHIF) and North Khirasra Fault (NKHIF), Netra fault (NF) and other cross faults from the western part of the Kachchh basin. Sub-seismic pure compaction deformation bands, cataclastic deformation band clusters, slipped deformation bands and deformation band faults were documented in the present study from porous Cretaceous Bhuj and Jhuran sandstone. These tabular structures are densely populated in the fault damage zones of aforementioned faults. In the Saurashtra peninsula, E-W trending, striated Katar fault (KF) offsets NE-SW trending dyke swarm belonging to the Deccan Trap.

A total of 1258 fault-slip data consisting of fault plane and slickenside attitudes along with kinematic indicators were recorded from 69 stations. They were analysed for paleostress analysis using Win-Tensor (v.5.8.8) and T-Tecto Studio X5 by executing the Right Dihedral Method. 20–30 m long, 2D and 3D GPR radargrams tracked the blind faults and deformation bands. The GPR data reveals that the intra-uplift faults are steep SW dipping reverse faults in the Kachchh basin and KF as south dipping revere fault in Saurashtra. The paleostress analysis results indicate stress regime index (R') range 2–2.75 and 0.25–0.75 suggesting transpressive to pure compressive and pure extensive stress regime respectively. SH_{max} trends ~NE to N in both the structural domains.

The Cenozoic deformation history in western continental margin of the Indian plate has been dominantly controlled by intraplate compressional stresses induced by anticlockwise rotation and collision of the Indian plate with the Eurasian plate at ~55 Ma. The Kachchh basin, where rifting aborted during the Late Cretaceous, accommodated syn-rifting extensional component in the intra-uplift faults. It has, then, undergone inversion phase due to onset of compressive stresses during the Post-Deccan Trap time up to the present. The NW-SE trending intra-uplift faults were reactivated multiple times and generated deformation bands that introduce high porosity contrasts with the host Bhuj and Jhuran sandstone. The Saurashtra horst, after the Deccan volcanism, also experienced the Cenozoic transpression component as exemplified by dominant reverse movement with sinistral slip along the KF.

A comparative analysis of rift faulting and underlying domal basement reflections at the Frøya High, offshore Mid-Norway

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It is well known that pre-existing structural grain may affect later rift fault formation and geometries. We here use seismic reflection data to investigate the relationship between domal reflections in the granite basement of the Frøya High (Mid-Norwegian Continental Shelf) and their relationship with the Klakk Fault system, which flanks the Frøya High to the west. We characterise the basement reflections as well as the southernmost part of the Klakk Fault Complex (KFC), which formed during the late Middle Jurassic to earliest Cretaceous, and separated the Frøya High from the Rås Basin to the west.

In the study area, two first-order fault segments comprise the KFC, with NE-SW and NW-SE orientations, with heave ranging from 10 to 17 km respectively, and lengths of approximately 35 km. The two fault segments intersect at a protrusion/salient on the western side of the Frøya High. In cross-section, the faults are comprised of a lower, listric, low-angle part, and an upper, heavily degraded fault scarp. Within the basement footwall of the KFC, we identify a series of high amplitude, low frequency, locally continuous reflections. We mapped two high-amplitude reflection packages in the basement that define i) a 4.4 km by 3.8 km dome-shape near the intersection of the northern and southern Klakk segments and ii) a NW-trending, NW-plunging anticline (length: 13.1 km; width 8.7 km) trending parallel to the southern KFC segment.

We hypothesize that the reflection packages represent structures in the basement that influenced the geometry and evolution of the KFC. We argue that the domal basement shape in the vicinity of the intersection of the northern and southern Klakk segments may have influenced the segmentation of the KFC, and that the NW-trending basement anticline may have influenced the orientation of the southern Klakk segment.

Although we cannot determine the origin of the basement reflection packages, we hypothesize that they may represent i) ancient orogenic or extensional shear zones, ii) intrusions, or that iii) the domal and anticlinal structures may represent the remnants of a metamorphic core complex at depth within the Frøya High. This would be consistent with the presence of several metamorphic core complexes in other places along the Norwegian margin.

The Use of GIS in the Spatial, Geometric and Topological Analysis of Fracture Networks: Presenting NetworkGT

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Dimensions, arrangements, and interactions of individual fractures form fracture networks that control the mechanical and fluid flow properties of rock masses. In subsurface exploration and production, it is critical to understand the geometrical as well as topological (i.e. connectivity) characteristics of the entire fracture network. Hence, analogs of natural two-dimensional fracture networks from remotely sensed imagery and/or outcrops are common to capture sub-seismic fractures that are important for fluid-flow behaviour. In the last decade, analogs of fracture networks have significantly improved with accessibility to large volumes of freely available data, improved data acquisition methods and higher resolution models. However, while the volume of analog data has sustainably increased, methods to quantitatively analyse and visualise geometry and topology of large fracture networks lacks.

Here we present NetworkGT, a toolbox designed to efficiently sample, analyse and map the geometrical and topological attributes of two-dimensional fracture networks. The algorithms are available in a Geographical Information Systems (GIS) framework providing structural geologists an ability to easily map and analyse large fracture network analogs for fracture length distributions, orientations, frequencies and ternary topology plots. To illustrate the potential and practicality of the toolbox, we apply the workflow on a fracture network example from offshore NW Devon, U.K. The fracture network is sub-sampled into 1326 regions to analyse and visualise the spatial variability in a range of geometrical and topological properties of the network. The NetworkGT toolbox allows for new opportunities to analyse the geometry and topology of fracture networks at a range of scales important for the assessment of water, geothermal, hydrocarbon and CO_2 reservoir viability.

The evolution of normal fault arrays in a rift basin: example from the Thebe field, NW Australia

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Stretching of the continental lithosphere causes thinning, which is accommodated by the development of large, linked, normal fault arrays. The early stages of rifting are fundamental to rift geometry and plate tectonics, however, the dominant controls driving extension are not fully understood. In order to better understand strain distribution during the growth and linkage of normal fault arrays, we use 3D seismic reflection and borehole data from the Thebe gas field, Exmouth Plateau, NW Shelf of Australia. This study area can be considered to have only experienced a single-phase extension (from Upper Triassic to Late Jurassic) with excellent quality seismic imaging allowing us to quantify the geometry and displacement history of entire, large scale fault arrays.

We interpreted ten regional seismic horizons defining key tectonostratigraphic units, eight of which are located in the syn-rift sequence. We combined time-surface maps with multi-attribute analysis in order to accurately define the structural framework. The study area is characterised by a main population of west dipping, NE-SW striking normal faults, with a smaller secondary population of N-S to NNW-SSE striking, low displacement faults. In the first fault population, five major fault systems are identified, with total fault trace lengths up to 45 km with throw values up to 600 ms TWT (~750 m). These fault systems cross cut pre-, syn- and post-rift mega-sequences, forming a series of tilted fault blocks in the Triassic Mungaroo Formation.

Here we use isochron and fault displacement backstripping to qualitatively and quantitatively record the evolution of fault patterns. Our results show that fault trace lengths were established early in rift history (in the first 12 Myrs) and strain progressively localises onto larger faults during extension. Fault displacement backstripping suggests that a significant proportion of displacement is gained within the earliest resolved slip increment (up to 300 ms TWT). However, the amount of throw accrued along the segments of major fault systems are variable through time, suggesting that fault linkage may occur progressively throughout rifting.

Deformation band formation in function of progressive burial: depth calibration and mechanism change in the Pannonian Basin (Hungary)

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Deformation bands (DB) are ubiquitous strain localization structures (Aydin, 1978) that are widespread in Miocene pre- and syn-rift sediments of the extensional Pannonian Basin, central Europe. Field examples from 16 outcrops represent disaggregation and cataclastic DBs (by classification of Fossen et al., 2007) and evidence of frequent reactivation by discrete faulting. Thin section analysis, cross-cutting relationships and well-defined time constraints demonstrate that in line with burial depth DB deformation mechanisms progressed from granular flow to increasing amount of cataclasis. Intersection of time spans derived from classification of DBs into 10 deformation phases and subsidence curves constructed for each deformed stratigraphic level used to unravel the depth intervals of each DB generation and subsequent structural element. The possibility of finer temporal resolution is due to favorite local structural evolution including frequent and rapid changes in the direction of fault and deformation band sets (Fodor et al., 1999; Petrik et al., 2014). Then, the formation depth of different DBs was transferred to the depth range of the related mechanisms. This combined methodology permits a more quantitative determination of deformation mechanisms with depth.

Our results show us that granular flow (disaggregation bands) dominates down to 100–150m as the earliest deformation structure, followed by weak then moderate cataclasis. The transition between weak and moderate cataclasis is approximately 300±100m for host rock rich in feldspar or fragile volcanoclastic components and from around 900±100m in quartz-rich sediments. Deformation by frictional sliding concentrated on discrete fault planes at the margin of cataclastic bands or on new fracture planes generally started from ~500±100m in volcanoclastic or feldspar-rich and 1000±100m in quartz-rich host rocks. Thus we suggest that burial-induced diagenetic processes contribute to the transition from moderate or advanced cataclasis to discrete fault slip.

Furthermore, the comparable examples of DBs from variable lithologies revealed that mineralogy is not so important in near-surface or very shallow conditions during disaggregation band formation. However, the role of lithology becomes more pronounced during burial. Shallowly buried volcanic fragment and feldspar-dominated host rock display a greater intensity of cataclasis than quartz-rich siliciclastics in similar depth.

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3-D complexity and imaging of crustal-scale normal faults – observations from the Vette Fault, northern North Sea

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The crust accommodates stresses by movement along discrete faults and shear zones. Studying the 3-D geometry and deformation styles of these structures is vital to our understanding of continental extension and seismic hazards, as well as for informing many geodynamic models, yet we are often unable to image the full extent of these structures in-situ.

Field studies may provide detailed insights into the internal structure and dominant deformation mechanisms of faults and shear zones where they are exposed at the surface; however, they are limited by available exposure and unable to reveal their large-scale, three-dimensional geometry. In contrast, seismic reflection data can offer unparalleled 3-D imaging of faults, particularly at shallow depths; however, the imaging of deeper, crustal-scale faults is often limited to sparse 2-D observations and at the expense of resolving the shallow structure. As a result, we rarely get images of large-scale fault geometry and structure. Conceptual and theoretical models are thus pieced together from observations of fault behaviour at different depths and at different scales, with limited observations from entire crustal-scale faults.

In this study, we use a 3-D broadband seismic survey from the northern North Sea, which offers excellent seismic imaging down to depths of 22 km (8 s TWT). This allows us to analyse the 3-D geometry, growth history and seismic expression of a major crustal-scale fault (Vette Fault) from the brittle upper crust down to the ductile lower crust. At shallow depths (< 2.5 s TWT) the fault is imaged as a discrete discontinuity defined by reflection terminations and is comprised of three distinct segments separated by relay ramps. Localised depocentres are identified within the hanging wall of the fault and align with prominent corrugations along the shallow fault plane. At deeper levels (~3 s TWT), the individual fault segments merge to form a single structure, imaged in the data as a prominent ~100 ms thick reflection that widens with depth, implying a thickening of the fault zone. Deeper still (~6 s TWT), the seismic expression of the fault plane disappears, before reappearing in the lower crust (6.5-8 s TWT) as a series of inclined reflections interpreted as a ductile shear zone. We suggest the region where the seismic expression of the fault is absent corresponds to the brittle-ductile transition in the crust.

This study describes the 3D geometry of a crustal-scale fault, from a brittle, segmented structure in the upper crust, to a wide shear zone in the ductile lower crust. These observations have fundamental implications for the geometry and evolution of faults, and allow us to link the seismic expression of a fault to fundamental depth-dependent deformation mechanisms operating throughout the crust.

Fingerprinting structural inheritance – Its styles and expressions in rift systems

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A range of structural heterogeneities are ubiquitous throughout the earth's lithosphere across all scales; accordingly, these heterogeneities display a range of interactions with rift-related faults, exerting variable influence over the development and evolution of rift systems. Due to difficulties in resolving these structures in the subsurface, perhaps due to lack of exposure/data, overprinting of later tectonic events, or the large-scale nature of the heterogeneities, we lack a detailed understanding of their influence and particularly the mechanics of their interactions with rifts and fault systems.

Although the heterogeneities themselves may be difficult to resolve in the subsurface, they likely leave some expression in the resultant, and likely better-imaged, rift system. The goal of this project is to understand how structural heterogeneities are expressed within rift systems, particularly where the heterogeneities themselves are unable to be resolved. Using a series of carefully chosen case-studies we will catalog the different styles of structural inheritance observed in rift systems. Based on this, we intend to replicate these interactions through numerical modelling techniques in order to better understand the controls on these different styles of structural inheritance. Finally, we intend to analyse rift systems and fault networks in order to extract any potential diagnostic characteristics of various styles of structural inheritance.

Here, we present preliminary findings of different styles of structural inheritance from a series of case-studies worldwide. Offshore New Zealand, in the Great South Basin, we document a series of different inheritance styles; at the small scale, pre-existing fabrics related to igneous activity and rotated sedimentary strata control the geometry of individual faults. At the larger-scale, basement terranes of varying strength, including the offshore extension of the Median Batholith, control the rift physiography and appear to inhibit fault propagation. Staying in the southern hemisphere, the Laminaria High on the NW shelf of Australia comprises a multiphase network of faults of varying orientation. The presence of anomalously oriented faults with respect to the imposed stress field indicates the presence of structural heterogeneities at depth. Elsewhere, in the North Sea, a Devonian Basin situated along the western margin of the Viking Graben has experienced a complex evolution. This long-lived basin displays multiple phases of activity, including later inversion. The potential presence of a granitic body in the area may have perturbed the geometry of the Viking Graben in this area.

In this study, we highlight the range of different structural heterogeneities that are able to influence rift systems and offer a series of initial insights into the styles of structural inheritance that may be present within rifts.

Fold growth in the South Caspian Sea Basin: Mechanisms and interaction with deep-water lacustrine sediments

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In comparison to salt tectonics, the mechanisms of mobile shale tectonics have been relatively poorly studied. Using a 3D reflection dataset, we investigate the growth of a shale cored detachment fold in the South Caspian Sea Basin (SCB).

The SCB is a unique basin in which 10 km of sediment has accumulated within the last 6 million years, overlying a thick, organic rich overpressured shale (the Maykop Formation). Shale cored anticlines and associated mud volcanoes have formed within the basin, with the Maykop Shale (>10km deep) acting as the detachment.

A 1600km^2 3D seismic cube used for this study images two anticlines (Shafag-Asiman fold structure) and three mud volcanoes. There are no well data and therefore horizons were interpreted based on seismic stratigraphy. We interpret 17 horizons from four stratigraphic sequences. Isopachs were created and alongside growth index analyses were used to evaluate the growth of the folds both spatially and temporally. Initial results show that whilst both folds appear to show similar growth patterns, growth varies between the limbs of individual folds and between the two folds. Regional tectonics suggest that Arabia-Eurasian N-S convergence produced the folding, however results show that a strike slip component is also present, causing the development of dextral en-echelon normal faults and a fold axis rotation through time. The dynamic nature of the fold growth may be due to a combination of both complex tectonic processes and the creation of accommodation space through mobile shale withdrawal during sediment loading, as observered with salt tectonics.

A Comparison of Fault Growth Models: Examples from Block-21, Offshore Angola

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Normal fault arrays accommodate crustal stretching and are a primary mechanism for active rifting and the structural evolution of extensional basins. In such settings, occurrence of normal faults which exhibit significant lengths and large total displacements is typically achieved through the linkage of smaller, precursor fault segments. Key stages of development associated with this style of normal fault growth are i) fault tip propagation where fault tips do not interact; ii) underlap and; iii) overlap, in which the bedding is reoriented and tip interaction produces relay ramp geometries and; iv) hard linkage of fault segments where the relay ramp is destroyed and a single coalesced fault is produced.

Fault growth models state that these processes occur either by (i) rapid establishment of length and subsequent accumulation of displacement (constant length model) or by; (ii) coeval increases in length (L) and displacement (D) (propagating fault model). These established models give two different kinematic scenarios and present very different predictions for fault evolution and array development. Consequently, constraining the physiography of continental rifts, sediment supply to and reservoir deposition in half-graben depocentres, and the timing of trap development is heavily dependant upon the predictions of these different kinematic scenarios.

We utilise a depth-converted 3-D seismic reflection dataset Offshore Anogla, Block-21, to present a comparison of these two modes of fault growth and undertake a quantatative analysis of displacement distribution in an extensional array. By comparing and contrasting observed characteristics in our results we interpret fault evolution and kinematics for natural normal faults. Finally, we discuss the implications of models for relay zone development and segment linkage during array development.

How do normal faults grow?

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Normal faults grow via synchronous increase in displacement and length ('propagating fault model', also known as the 'isolated fault model'), or by rapid length establishment and subsequent displacement accrual (constant-length fault model). We here use time-series displacement (D) and length (L) data from natural and experimental faults to elucidate growth styles and D-L trajectories throughout fault life, and to assess the applicability of the two fault models. We show that the growth of most faults is characterized by two stages, with the first defined by fault lengthening (20-30% of fault lifespan) and the second by displacement accrual (70-80% of fault lifespan). Although broadly adhering to the constant-length model, fault growth throughout the lengthening stage, during which significant displacement (10-60% of the total end-of-life fault displacement) may also accumulate, is achieved through rapid tip propagation, relay breaching, and segment linkage, characteristics perhaps most intuitively thought to reflect growth in accordance with the propagating model. The subsequent growth stage is dominated by displacement accrual with limited lateral tip propagation, a phenomenon best described by the constant-length model. We also show that, despite being used primarily in support of the propagating model, global displacement-length (D-L) datasets are equally compatible with the constant-length model.

Asymmetric continental deformation along the South Atlantic and its influence on Large Igneous Province emplacement

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Kinematic plate reconstruction models demonstrate that South America and Africa do not fit perfectly when restoring the continents to their pre-breakup position, a misfit commonly solved by considering intra-plate deformation zones within South America. Many kinematic models implement such a zone at the latitude of southern Brazil, despite poor geological indications for a distinct deformation structure in this region. Southern Brazil also receives significant scientific attention as it is covered by the voluminous Paraná-Etendeka Large Igneous Province, which derived from the Tristan da Cunha hot spot and whose preserved remains span across 917,000 km^2 in South America, and 78,000 km^2 in Namibia. Both the age relationship of the lava emplacement with the South Atlantic rift and the location of the Tristan da Cunha hotspot during emplacement are subject to continuous debate.

Here, we present a synthesis of data published throughout the last two to three decades on various geological aspects of Namibia and southern Brazil, which pictures an asymmetric tectonic evolution of these regions. This includes aspects of basement reactivation during rifting, fault patterns, and dyke emplacement. Magma flow directions in dykes, as well as stratigraphic and geophysical studies indicate a hot spot location in or near the rift center. Based on this data, we present a breakup model (Salomon et al., 2017) and argue for significant rift-parallel extension on the South American side that is not confined to a distinct deformation zone in southern Brazil, but distributed across ~1000 km along the margin. This extension is inferred to result from a clockwise rotation away from stable Africa and stable northern South America, in a similar fashion as it has been proposed for Patagonia (e.g. Koopmann et al., 2013). Subsequently, widespread pathways were created for dyke intrusions in Brazil, Paraguay, and Uruguay causing the massive outpour of lavas on the South American side, while the center of the hot spot was located in or near the rift. Consequently, the data and our model also emphasize a syn-rift relation of the lava emplacement, with their spatial distribution guided by large-scale tectonic plate movements.

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Dyke reactivation across the frictional-viscous transition: Insights from Precambrian deformation of Scourie dyke margins in NW Scotland

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Basement-hosted regional dyke swarms are recognised worldwide, representing anisotropies at a lithosphere-scale that may considerably influence later deformation. Precambrian deformation events have affected the Lewisian Complex of NW Scotland, with Badcallian (ca. 2.75 Ga) and Inverian (ca. 2.5 Ga) events predating, and Laxfordian (ca. 1.75 Ga) and 'Late Laxfordian' (ca. 1.55 Ga) events post-dating the regional Scourie dyke swarm (ca. 2.4 Ga). The present study focusses on Scourie dykes within the Assynt Terrane with a variety of contact relationships and reactivation styles. Contacts between mafic dykes and Lewisian gneisses were studied to assess the extent of reactivation, and to determine cross-cutting relationships. *Lochinver (NC087219):* Moderately dipping dyke margins preserve undeformed intrusive contacts, including a 1.5cm chilled margin. *Achmelvich (NC056250 and NC055248):* Two localities preserve different reactivation styles. 'Achmelvich North' preserves local developments (<1.2m) of schistose mylonites with dextral shear sense indicators in mica schists, with syn-tectonic quartz mineralisation. The styles of deformation, veining and associated metamorphism are consistent with Laxfordian deformation in the nearby Canisp shear zone. 'Achmelvich South' preserves schistose viscous mylonites at the southern dyke margin, but the northern margin preserves a complex history of localised ductile and later brittle reactivation. The latter is associated with pseudotachylytes parallel to the dyke margin (Fig. 1) and as injections into the surrounding gneiss. Shear sense indicators for brittle deformation and associated calcite+zeolite mineralisation are consistent with sinistral shearing. *Loch Assynt (NC2125):* Sharp, brittle dyke margins show evidence for localised (1-5cm) sinistral ultramylonites and micrometre pseudotachylytes at the dyke margins, overprinted by later brittle sinistral reactivation. Both ductile and brittle deformation is associated with widespread epidote and localised copper mineralisation. The latter constrained to ca. 1.55 Ga by rhenium-osmium sulphide geochronology. Thus, field and microstructural observations provide evidence for at least three phases of brittle-ductile reactivation along dyke margins. These are broadly correlated with Laxfordian and 'Late Laxfordian' regional events; the reactivation suggests that structural inheritance plays a key role in the reactivation of basement complexes.

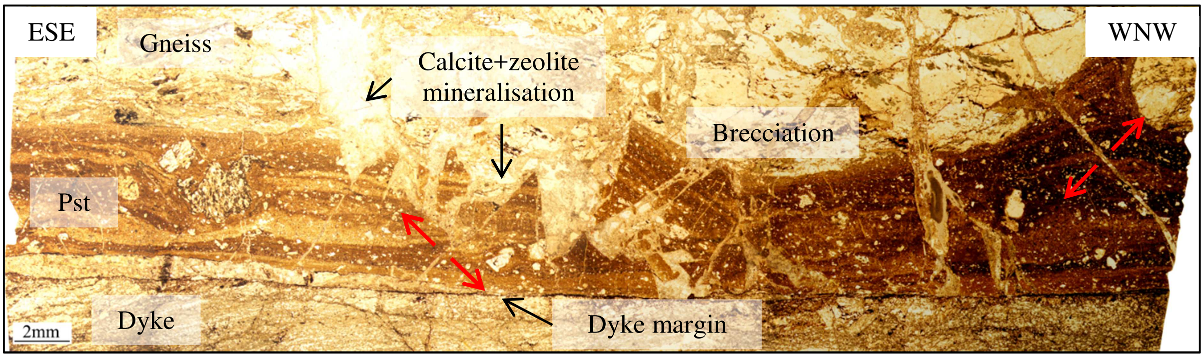

Fig 1: Achmelvich South (northern margin). PPL section showing pseudotachylytes (pst) and associated features at the dyke margin.

Microstructural and Physiochemical Processes Influencing Fracture Sealing in Geothermal Systems

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Geothermal power offers a sustainable source of clean energy, and such resources are constantly developing as the global community moves progressively towards diverse energy portfolios. Heat and fluids circulate within many hydrothermal systems through an interconnected structural network. Given time and a range of thermodynamic and physical property evolutions in these circulating fluids, minerals nucleate and grow within this plumbing system, often accumulating on fracture walls, e.g. scaling and vein minerals. As this process continues, eventually the structural fluid flow network can become sealed against further transport. This has a negative effect on the efficiency of a geothermal resource, slowing or stopping flow and reducing overall productivity.Therefore, it is imperative that we understand the interwoven chemical, mechanical, thermodynamic and hydraulic factors which govern fracture sealing, from macroscale processes down to nanoscale behaviour. This research proposes to investigate the factors which influence fracture sealing in hydrothermal/geothermal systems, by carrying out a detailed analysis of microstructural character in mineralised vein samples. Natural observations will be compared against numerical models of hydrothermal mineral growth within a vein setting to attempt to determine which processes facilitate mineral nucleation and growth. The study has sourced numerous field and industry samples from a range of hydrothermal settings in Uganda, New Zealand and Iceland, including active geothermal fields and epithermal veins, to better understand the potential range of mechanisms controlling mineralisation in structural fluid flow pathways.

Electron backscatter diffraction carried out on a number of Calcite veins from the Kibiro geothermal reservoir, Uganda, provides some interesting preliminary data. Initial results show that calcite crystal growth exhibits a preferential crystallographic orientation on sites where nucleation occurs on pre exisiting adularia crystals. This could indicate the preferable template offered at locations where adularia is occuring serves as a potential control for calcite growth processes.

Structural controls on the geometry of the Curraghinalt gold deposit, Northern Ireland: Implications for the Grampian Orogeny

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The Curraghinalt gold deposit (>3.06 Moz Au) is located in the Sperrin Mountains of Northern Ireland. The high-grade mineralisation (15.01 g/t Au) is hosted by a series of west-northwest trending, moderately to steeply dipping, stacked quartz-carbonate-sulphide veins with short and narrow extensional veinlets (Dalradian Resources, 2018). The lode-gold deposit is hosted by Neoproterozoic metasediments (Dalradian Supergroup, Grampian Terrane) which were thrusted southeast over an island arc (Tyrone Igneous Complex, Midland Valley Terrane) in the early to mid-Ordovician during the final compressional phase of the Grampian Orogeny (Aslop & Hutton, 1993a). Recent geochronological dating has confined the emplacement of the gold-bearing mineralisation at Curraghinalt to a short ca. 10 Ma interval in the lower Late Ordovician (462.7–452.8 Ma), inferred to be related to the post-orogenic collapse of the hangingwall pile (Rice et al., 2016, Aslop & Hutton, 1993b). The crustal profile of metasedimentary rocks overlying a still hot island arc is thought to have produced a large and long-lasting hydrothermal system, allowing the rapid release of crustal orogenic fluids to derive heat, metals, and some fluids from the underlying arc (Rice et al., 2016). It is notable, however, that a number of previous studies have proposed a significantly different genesis for the Curraghinalt gold deposit, with two distinct gold-mineralisation episodes inferred from cathodoluminescence, fluid inclusion studies, and stable isotope geochemistry (Wilkinson et al., 1999, Parnell et al., 2000): (1) the gold was primarily emplaced in the late-Caledonian, with magmatic fluids related to Siluro-Devonian intrusive activity exploiting pre-existing Grampian structures; (2) The remaining gold was emplaced during a remobilisation event related to low-temperature, high-salinity basal brines in the Carboniferous, linked to basin inversion during the Variscan Orogeny. Here, we present preliminary results from a deposit-scale structural study of the Curraghinalt gold deposit, as well as regional-scale structural study incorporating other important gold localities (e.g. Cavanacaw gold deposit, ~20 km to the southwest), to provide insight into the relative timing(s) of gold emplacement in relation to the tectonic evolution of the Grampian Terrane. Using the data collected from underground geological mapping, drill core analysis, and microanalytics, we present detailed structural models of the Curraghinalt lode-gold system that reveals the internal geometry of the vein zones and predicts the relative timing(s)/stress regime(s) responsible for gold emplacement. From surface geological mapping, drill core analysis, and a renewed interpretation of the Tellus airborne geophysical survey, we also propose a new regional-scale tectonic model that suggests that other important gold localities in the region (e.g. Cavanacaw gold deposit, Rylagh gold prospect) are genetically related to the Curraghinalt gold deposit, despite differences in vein orientations, textures, and ore mineralogy. Gold was most likely emplaced in the lower Late Ordovician as previously proposed for Curraghinalt (Rice et al., 2016), though rather than being related to a post-orogenic collapse episode, the potential role of syn-orogenic collapse during arc-continent collision is also discussed.

A revised palaeogeography of the Falkland Islands microplate based on offshore seismic and gravity data

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The tectonic complexity of transform margins can hinder their palaeogeographic reconstructions. The example considered here is the Falkland Plateau. Its position, along with that of the Falkland Islands, within a Gondwana pre-break-up configuration has been a subject of debate for decades. This impacts our understanding of the evolution of the plateau and it also influences the reconstruction of Southern Gondwana.

Previous reconstruction models argue for a pre-break-up position of the Falkland Islands micro-continent offshore south-eastern South Africa, as part of a rigid plateau or rotated by ~180°. The scarcity of crustal-scale information about the basins around the Falkland Islands hampers a direct comparison between the plateau and South Africa.

This study provides new insights into the evolution of the plateau, by integrating seismic reflection and gravity data from the Southern North Falkland Basin (SNFB). This allows us to better assess the geometry of the NW-SE striking reactivated thrusts bounding the half-grabens of the SNFB. These have shallow depth-converted dips between 25° and 50°, lengths of up to 150 km and up to 5 km throws. On the conjugate South African margin, the faults bounding the offshore sedimentary basins show consistent shallowing of dip north-eastward from 60° to 24° and a change in strike from WNW-ESE to NNW-SSE eastward thought to follow the inherited crustal fabric of the Cape Fold Belt. The architecture of the SNFB shows most similarities with the northernmost Outeniqua Basin.

We propose that the reactivated thrusts from the South African basins and the SNFB developed along strike from each other. This implies that prior to break-up the Falkland Islands were situated in a more southern position than previously suggested. The revised reconstruction yields ~140° of rotation and predicts more unstretched crust east of the islands than previous models and can impact future reconstructions of the Southern Gondwana.

Sill geometry as a record of horizontal compression

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Igneous sills and dikes represent an important component of the deformational history in volcanic settings. Like dikes, sills are traditionally thought to propagate as Mode I hydrofractures, i.e. parallel to the σ_1-σ_2 plane. However, unlike dikes, sills are typically omitted from tectonic studies and paleostress analyses. The close spatial association between sills and dykes in layered host rock (e.g. sedimentary basins, or volcanic lava piles), has led to many models that suggest sills are fed by dikes. Such models require a local rotation of the minimum principal stress axis (σ_3) from horizontal (for dikes) to vertical (for sills). This can be achieved in a low deviatoric stress state (i.e. where $\sigma_1 \approx \sigma_2 \approx \sigma_3$), where mechanical stratigraphy can induce local stress perturbations, and pre-existing discontinuities (i.e. bedding, faults, or joints) of any orientation may be dilated and intruded. These models, however, do not account for sill geometries that transgress through horizontal or vertically bedded strata.

In order to address the role of host rock layering on intrusion geometry we present the results of detailed field studies from two sill complexes; the Loch Scridain Sill Complex (LSSC), Isle of Mull, UK; and sills in the San Rafael Sub Volcanic Field (SRSVF), Utah, USA. In both examples sills have consistent low-angle dips between 1° and 25°. Sills in the LSSC cut through vertically layered and foliated metasedimentary basement, and horizontal sedimentary and volcanic cover units. Sills in the SRSVF cut through near-horizontal sedimentary units; notably, regional-scale sills cut formation boundaries at a low angle. In both cases the sills either cut, or are cut by dikes, and no clear *feeder* dikes were observed in either region. The LSSC and SRSVF sills display low-angle opposing dips, which generally give a bimodal dip distribution. In some instances intersecting sills of opposing dips cross-cut or are linked, and accommodate coaxial vertical uplift of the host rock. In both study areas the sills cut or abut against steeply dipping faults, fractures, and foliation; from this we infer that the magma pressure was less than the horizontal stress at the time of emplacement. To better constrain the stress state during sill emplacement we analyse the overall and local sill attitudes with mechanical models of slip tendency and dilation tendency. We also present a new depth independent mechanical model that uses local sill attitudes and opening angles to derive the stress ratio and relative driving pressure at the time of emplacement.

Our results indicate that in both study areas host rock layering did not present the primary control on the location of sill emplacement or sill geometry. Alternatively, sills in the LSSC record periods of near-radial horizontal shortening, related to the superposition of the regional tectonic stress and local volcano construction-induced stress; while sills in the SRSVF appear to relate to previously unrecognised periods of tectonic shortening, and potentially, the reactivation of major regional-scale faults.

Intraplate deformation offshore North Sumatra: New Insights from integration of IODP Expedition 362 results with seismic data

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The deformation at subduction zones can induce deformation within the incoming plate hundreds of kilometres away, creating large-scale distributed deformation zones which can influence the formation of subduction zone fault structures and affect the hydrology of the plate. Determining the nature, geometry and physical properties of the oceanic lithosphere is an important constraint in understanding the mechanics of this deformation, and ultimately the subduction process.

The northeast Indian oceanic plate and overlaying sediments are pervasively deformed by re-activated fracture zones and a related system of conjugate faults that are confined to the sedimentary section. These faults are likely related to subduction-related flexure, distal India-Eurasia collision and other less well constrained processes. IODP Expedition 362 sampled the entire sequence of sediments on the oceanic plate offshore northern Sumatra, ~225 km seaward of the subduction zone deformation front. We re-evaluate 2D multichannel seismic reflection profiles that crosscut the Expedition 362 U1480 and U1481 boreholes and assess the variation in fault displacement patterns between the Ninety East Ridge and the Sunda subduction zone.

We also couple the seismic observations of fault displacement and activity with IODP borehole lithological, physical properties and structural data to assess the influence of sediment properties and constrain timings of fault activity. Faults that dip towards the subduction zone (landward-dipping) accommodate a greater amount of normal displacement relative to seaward-dipping faults, and the dominance of the landward-dipping faults for displacement increases with proximity to the deformation front.

Maximum fault displacements occur ~7 Ma in the vicinity of the boreholes, coinciding with the lithostratigraphic subunit IIB-IIC boundary, a change from sand- to mud-dominated fan sediments. We note that the depth of maximum fault displacement increases with proximity to the deformation front. There is a correlation between fault propagation and sedimentary channels, whereby channels inhibit the upward propagation of faults. We conclude that brittle deformation in this part of the Sumatra input section is a combination of shearing on reactivated fracture-zones, plate flexure, sediment properties and the architecture of the Nicobar fan. The lack of basement offset suggests these faults play a minor role in oceanic crust hydration during pre-subduction times.

Fault reactivation and superimposed basin development: onshore insights from the Inner Moray Firth Basin, Scotland

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Many sedimentary basins worldwide are superimposed partially or completely over pre-existing basins. In such cases, the role of inherited structures is commonly difficult to constrain due to the limited resolution of seismic data or lack of surface exposure. Yet a better understanding of how earlier-formed faults localise deformation and interact during rifting can give key insights into basin development and reduce sub-surface uncertainties. The E-W striking Inner Moray Firth Basin (IMFB) lies in the western part of the North Sea trilete rift system formed mainly in the Upper Jurassic. The IMFB has experienced a long history of superimposed rifting and inversion. It is partially developed upon the pre-existing Devonian-Carboniferous Orcadian Basin and a regionally developed Permo-Triassic rift system. The role of inherited Devonian-Carboniferous brittle faults in basin development and their influence on the kinematics of later basin opening remains unclear. Onshore fieldwork was carried out along the southern coast of the IMFB to gain an insight into faulting and associated structures cross-cutting Devonian sedimentary units. This helps better constrain the earlier kinematic history of the IMFB and reveals the sub-seismic structural style around reactivated faults. These findings can then be used as a template for sub-surface offshore interpretation of the IMFB.

The study area is characterized by: i) N-S to NE-SW striking faults and fractures, with fault panels showing normal-sinistral lineations and normal-dextral slickenfibres, respectively; ii) WNW-ESE to NW-SE sinistral fractures and faults, and iii) N-S to NNW-SSE trending folds. The normal-sinistral faults are syn-sedimentary based on the widespread preservation of growth strata. The faults develop at high dips (up to 70º), but are progressively rotated to shallower angles with increasing displacement. Normal-dextral slip along N-S to NE-SW and sinistral slip along WNW-SSE to NW-SE faults are consistently associated with calcite mineralization (e.g. calcite-cemented fault breccia, tensile veins or Riedel shear fractures). The folds are generally open and plunge gently NW. They become tighter, moderately plunging (40º) and the hinge line rotates towards a more N-S azimuth close to major faults. The N-S to NE-SW striking growth faults are related to the opening of the Orcadian Basin. This suggests that the regional sinistral transtensional model recognised north of Great Glen Fault (on the NW side of the IMFB), extends to the southern limits of the Orcadian Basin in the Central Highlands. These trends have then been dextrally reactivated during NW-SE extension in the Permo-Triassic. Associated antithetic sinistral WNW-SSE to NW-SE striking faults and transtensional folds also develop at this time. Thus, the NW-SE opening of the IMFB leads to reservoir-scale structural complexity due to widespread oblique reactivation of earlier Orcadian Basin structures. This pattern is also seen in Caithness further to the north, but Jurassic and younger extension is less evident north of the Helmsdale Fault close to the NW margin of the IMFB. The findings here can be applied to other superimposed basins worldwide.

The Lærdal-Gjende fault (southwestern Norway): A new, high resolution, combined structural-geochronological study

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The Lærdal-Gjende fault is a major fault in southwestern Norway with a strike length of over 180 kilometres. The fault dips gently to the NW and has been reativated muliple times and is accomodated by predominantly NW extensional brittle faulting. At the sampled site in Lærdal, the fault is made of a several metres thick cohesive greenish cataclastic damage zone and approximately one metre thick gouge core, developed at the expense of mylonitic orthogneiss. The brittle component is generally believed to be the spatial, upward continuation of the Devonian Hardangerfjord detachment. This is one of number of large Devonian detachments, which was reactivated as an extensional fault at shallower structural levels to accommodate major top-to-the NW ductile shearing during the Caledonian orogenic collapse.

The Lærdal-Gjende faulting has been dated so far by paleomagnetic methods to be between Permian and late Jurassic-early Cretaceous in age (Andersen et al., 1999). Fossen et al. (2016) have further constrained the timing of fault slip to about 140 Ma using K-Ar illite analysis.

To better constrain the fault's complex evolution and to further refine the K-Ar dating methodology applied to synkinematic illite, we have collected, characterised and dated five samples. Detailed structural analysis included defining and sampling a coarse, angular cataclastic breccia (sample LG_GVI_4), an indurated red gouge (LG_GVI_6), a fine grained greenish gouge (LG_GVI_5), a more plastic, clay rich gouge (LG_GVI_7) and, finally, a very continuous and only a few millimetres thick brown clay smear found along the main slip surface (LG_GVI_8). Illite from all samples was separated into five different grain size fractions (10-6, 6-2, 2-0.4, 0.4-0.1, < 0.1 μm), each of which was also analysed by XRD.

Ages vary between 200 and 57 Ma with a strong correlation in age with grain size. The coarser fractions yield the older ages and the finer the younger ones. We take the age of the finest fractions of the samples as the most representative of the various faulting episodes accommodated by the fault. The finest fractions, mostly barren of inherited protolithic K-bearing phases and enriched in authigenic synkinematic illite, indicate up to four different slip episodes at 120, 87, 78, 57 Ma. The youngest age is from a fraction containing 30 % illite and 27 % K-feldspar, such that it has to be considered as a maximum age for the latest recorded increment of faulting along the Lærdal-Gjende.

Our new data provides an extraordinary, unprecedented temporal resolution of this fault slip history thanks to a careful, combined structural-geochronological approach. In detail, our results constrain the timings of fault movement along onshore southwestern Norway, down to the Paleocene. Moreover, our data questions Devonian and Permian activity along the fault, as previously suggested in literature.

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Strain Modification in Oblique Rift Settings: Evolution of the Late Jurassic Lomre-/Uer Terraces, North Sea Rift

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The increasing wealth of large-scale 3D seismic data revealed that many rift basins exhibit complex geometries caused by non-colinear normal fault systems. Changes in plate-divergence is often invoked to explain non-collinear fault systems in rifts. However, *local* modification of tensional stresses to cause local, lateral variations in extension directions between distinct structural domains has rarely been considered. Yet, as we show here, this may be a viable mechanism for the formation of non-colinear fault systems in rifts. The present study is based on the eastern flank of the Northern Viking Graben, where fault terraces evolved between a major intrabasinal platform and laterally segmented rift-axis grabens. Using an extensive well database and regional 3D broadband seismic reflection data, we investigate the kinematic evolution of the Lomre/Uer terraces, located on the eastern shoulder of the Northern Viking Graben, and introduce a hierarchy of controls modifying the local stress field in and around the Lomre/Uer terraces during the Late Jurassic rifting within the Northern North Sea.

The Lomre terrace consists of an approximately 25 km wide and 50 km long complex array of rotated fault blocks arranged in a conjugate architecture with significant stratal thinning towards its terrace centre. In turn, the southern part of the Lomre terrace exhibits fault block downstepping to the northwest. We grouped both terraces into three distinct structural domains: 1) strongly asymmetric and rotated syn- and antithetic half graben domain; 2) a domain of mostly symmetric internal terrace grabens with an rhombic normal fault system; and 3) the mostly unfaulted Uer terrace with localized strain on the terrace-bounding normal fault. Kinematic analysis (isopach analysis of syn-rift growth strata) shows simultaneous growth of NE-SW and N-S striking normal faults with later fault activity shifting onto major N-S oriented structures. The latter show reactivation of pre-existing N-S striking normal faults caused by prior extensional periods. The dominant NE-SW trend however is of thin-skinned nature and does not exhibit control of the underlying fabric. Analysis of branch lines within the rhombic fault systems on the Lomre terrace shows a clear modification of the local stretching direction from E-W in the adjacent platform and rift-axis graben to roughly NW-SE on the terraces.

We attribute the regionally consistent NW-SE trend to a modification of the greatest horizontal principal stress in structural domains that are located outside of the internal rift-axis graben. We suggest that this modification is essentially caused by the process of lateral graben segmentation, which in turn is caused by pre-existing basement weak-zones. Analogue and numerical modelling studies of oblique rifts have indicated that structures within internal graben areas strike orthogonal to the plate divergence. However, structures that are located outside of the main rift axis graben, the so-called rift-axis boundary, tend to be orthogonal to the mean of plate divergence (here E-W) and the orthogonal of the pre-existing rift weakness (here roughly NNW-SSE), giving an approximate stress field in NW-SE direction. This can explain the dominant NE-SW trend of Late Jurassic normal faults on the rift shoulder of the Northern Viking Graben. Additional control on the adjacent platform areas is exerted by underlying N-S striking structures from predating extensional events. These areas also exhibit diachroneity in peak fault activity, as the main phase of normal faulting post-dates those of faults in the terrace domains. In summary, we hypothesize that the dominant NW-SE trend on the Lomre/Uer terrace area was not caused by a rotation of the extensional direction, as suggested by previous authors, but by response to the right lateral stepping of graben segments modifying the local stress field in respective rift-axis boundary domains.

Ductile structures in basement windows of the SW Scandinavian Caledonides and their potential for brittle reactivation

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The Scandinavian Caledonides are the remnants of a large Paleozoic continent-continent collision orogen. The Baltican continental margin was subducted and subsequently exhumed in a post-orogenic extensional regime. The subducted continental crust is exposed today in basement windows in SW Norway. We present a structural comparison of two distinct windows, the Gulen culmination and the Øygarden Complex, that were dominated either by high pressure or high temperature, respectively. We will have a close look at different ductile structures that developed during Devonian post-orogenic exhumation and their variable potential for brittle reactivation.

The Gulen area represents the southernmost culmination of the Western Gneiss Region in the footwall of the Nordfjord-Sogn detachment zone. The area hosts the southernmost occurrence of eclogites in the basement, marking the extent of Caledonian high-pressure metamorphism. Shear zones formed preferentially in felsic lithologies during exhumation while eclogites were retrogressed. The area shows two distinct deformation domains: subvertical coaxial amphibolite-facies shear zones developed in the core of the culmination and indicate N-S shortening and E-W extension. Detachment mylonites formed on the flanks of the culmination and show non-coaxial fabrics, low-grade retrogression and vertical shortening.

The Øygarden Complex is a hotter basement window as witnessed by the occurrence of Caledonian migmatites and sillimanite-bearing gneisses. This window is characterized by very strong pervasive deformation and shallow dips. Most rocks show common properties of detachment mylonites, such as non-coaxial fabrics, fluid-assisted retrogression and vertical shortening.

Our discussion of the reactivation potential focuses on shear zone rocks and geometries. Detachment mylonites comprise weak rheologies such as phyllonites, however, they commonly appear to be cut by brittle faults because of their shallow dip. Subvertical high-grade shear zones, on the other hand, can show very straight trends over 10s of kilometers, which makes them prone to reactivation. Lateral strike-slip boundaries, like the northern Bergen Arcs Shear Zone, exhibit the highest potential for brittle reactivation because they combine steep dips, straight trends and weak lithologies.

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