2011 Meeting Programme

Tuesday 4th January

Pre-meeting workshop: *"Design of Rock Deformation Apparatus"*

Wednesday 5th January

09:00-12:00	***"Design of Rock Deformation Apparatus" Workshop***
09:00-12:00	***Registration & Poster setup***

13:00-13:10	***Opening address***

Session 1: Hazards & Tectonics 1	***Chair: Gerald Roberts***
13:10-13:30 (*Keynote*)	*Crustal Velocity Field from InSAR and GPS Reveals Internal Deformation of Western Tibet.* **Tim J. Wright** & H. Wang
13:30-13:45	*Crustal Deformation of the Central Tibetan Plateau Measured Using InSAR.* **Matthew C. Garthwaite***, T.J. Wright & H. Wang
13:45-14:00	*The Active Deformation Front of the Gobi Altai Transpressional Orogen, Mongolia: Insights Into Processes of Continental Interior Reactivation.* **Dickson Cunningham**
14:00-14:15	*Tectonic Evolution and Present-day Kinematics of the Palu-Koro Fault, Eastern Indonesia.* **Ian M. Watkinson** & R. Hall
14:15-14:30	*Discussion*

14:30-14:50	***Refreshments & Posters***

Session 2: Overpressure & Geomechanics	***Chair: Bob Holdsworth***
14:50-15:10 (*Keynote*)	*The Mechanical Implications of High Fluid Pressure Reservoirs at the Base of Seismogenic Zones: Observations and Modeling.* **Stephen A. Miller** & B. Galvan
15:10-15:30 (*Keynote*)	*Pore Pressure – Stress Coupling: Evidence from Deep Boreholes.* **Richard E. Swarbrick**, R.W. Lahann & S. O'Connor
15:30-15:45	*Development of a Fluid Flow Pipe Triggered by Lateral Pressure Transfer on a Sub-Circular Fold, Deepwater Niger Delta.* **Amélie M. Leduc***, R.J. Davies, R E Swarbrick, A.L. Densmore & J. Imber.
15:45-16:00	*Metamorphic fluid overpressures: experiments and a numerical model.* **J. Wheeler**, S. Llana-Funez & D. R. Faulkner
16:00-16:15	*Low Temperature Creep in Carbonate Materials: Effect of Reactive Fluids and Transient Deformations* **François Renard**

16:15-16:30	*Clast-Cortex Grains in Nature and Experiment: Fossil Earthquakes in Limestone?* **Steven A.F. Smith**, A. Billi, G. Di Toro, A. Niemeijer & E. Spagnuolo
16:30-16:45	*Discussion*

16:45-17:30	***Meeting Icebreaker & Poster session***

17:30-18:30	*The Role of Serpentinite in Generating a Weak, Creeping Fault: Evidence From Laboratory and SAFOD Investigations.* **Diane E. Moore**, D.A. Lockner & M.J. Rymer

Thursday 6th January

08:30-09:00	***Registration; Refreshments & Posters***

Session 3: Continental Margins 1	***Chair: Robert Wilson***
09:00-09:20 (*Keynote*)	*Extreme Crustal Thinning and Mantle Exhumation at Deep-Water Rifted Margins: the Lesson From the Iberia-Newfoundland and Alpine Tethys Margins and Applications to the pre-Salt Basins of the S-Atlantic.* **Gianreto Manatschal**
09:20-09:35	*The Deep Structure of the Porcupine Basin: Comparison with the W. Iberian Rifted Margin.* **Ken McDermott*** & T. Reston
09:35-09:50	*Evolution of the Rockall Trough: A Numerical Modelling Approach.* **Rosie Smithells***, S.S. Egan, S. Clarke, G. Kimbell, K. Hitchen & H. Johnson
09:50-10:05	*Controls on Passive Margin Evolution: A case study of the Santos Basin, Southeastern Brazil.* **David Ashby***, K. McCaffrey, R. Holdsworth & J. Almeida
10:05-10:20	*Role of Irregular Plate Margins in the Neoproterozoic-Cambrian Tectonic Evolution of the Brasília Belt, Central Brazil.* **Luiz José H. D'el-Rey Silva**, C.B. Pohren & I.L. de Oliveira
10:20-10:35	*Discussion*

10:35-11:00	***Refreshments & Posters***

Session 4: Fault Zone Development & Characteristics	***Chair: John Walsh***
11:00-11:15	*3D Modeling of Fracture Density and Connectivity Within Faulted Chalk Reservoirs – A Case Study From Flamborough Head, UK.* **David Sagi***, N. De Paola, K.J.W. McCaffrey, R.E. Holdsworth & R.R. Jones
11:15-11:30	*Development of a Multi-scale Fracture System Throughout the Cambro-Ordovician Sedimentary Succession in Southwestern Jordan.* **Geertje Strijker***, J. Klaver, F. Carranza, G.V. Bertotti & S.M. Luthi
11:30-11:45	*Characterising Fracture Systems on the Isle of Lewis: An Onshore Analogue for the Clair Field.* **Benjamin S. G. Franklin***, R.E. Holdsworth, K.J.W. McCaffrey, R.J. Walker, M. Krabbendam, A. Conway & R.R. Jones

11:45-12:00	*Predicting the Internal Structure of Fault Zones in Igneous Rocks and its Effect on Along-Fault Fluid Flow.* **Rachael Ellen***, Z. Shipton & R. Lunn
12:00-12:15	*The Origin and Nature of Cenozoic Faults and Dyke Swarms in North East Ireland.* **Hugh Anderson***, J.J. Walsh & M.R. Cooper
12:15-12:30	*Magmatically Driven Fault Growth, Afar, Ethiopia.* **Barbara Hofmann***, T. Wright, D. Paton & J. Rowland
12:30-12:45	*Discussion*

12:45-13:45	***Lunch & Posters***

Session 5: Energy, Resources & CCS	***Chair: Jon Gluyas***
13:45-14:05 (*Keynote*)	*Structural Geological Processes Controlling Distribution of Permeability in UK Coals.* **Jonathan Turner**
14:05-14:20	*CO_2 Dissolution From Inclined Fractures in Deep Saline Formations* **Francesca E. Watson*,** J. van Hunen, S.A. Mathias, R.R. Jones & S.E. Daniels
14:20-14:35	*Patterns in the Locations and Characteristics of Natural CO_2 Seeps in Italy.* **Jennifer J. Roberts***, A. Bell, R.A. Wood, P. Cowie, M. Edwards & R.S. Haszeldine
14:35-14:50	*Porosity and Permeability Evolution of Faults in a Sandstones Analogous Reservoir in the "Bassin du Sud-Est", Provence, France.* **Elodie Saillet** & C.A.J. Wibberley
14:50-15:05	*Hydraulic Implications of Shallow Faults Dominated by Particulate Flow.* **Sian Loveless***, V. Bense & J. Turner
15:05-15:20	*Discussion*

15:20-15:45	***Refreshments and Posters***

Session 6: Fault Timings & Kinematics	***Chair: Graham Leslie***
15:45-16:00	*The Kinematic Significance of Imbricate Faults within Thrust Sheets.* **John G. Ramsay**
16:00-16:15	*The Tectonic Evolution of the Lucanian Apennines of Italy: Structural Constraints from the High Agri Valley.* **Enrico Tavarnelli**, G. Prosser, F. Bucci, P. Guglielmi, R. Novellino & V. Pasqui
16:15-16:30	*An extensional piggyback model for large apparent displacements along major "thrusts": Examples from the Norwegian Caledonides.* **Simon J. Cuthbert** & H.K. Brueckner
16:30-16:45	Topology, Kinematics and Strain Variation Within Strike-Slip Fault Networks. **Casey W. Nixon***, D.J. Sanderson & J.M. Bull
16:45-17:00	*U-Pb Dating of Brittle Deformation.* **Martin Rittner** & W. Müller
17:00-17:15	*Discussion*

17:15-18:00	***AGM chaired by Prof. John Wheeler, & Drinks Reception***

18:00-19:00	*Global Exploration of Rifted Continental Margins and Micro-continents: Mapping Crustal Thickness and Ocean-Continent Transition Using Satellite Gravity Inversion.* **Nick J. Kusznir**

19:30	***Conference dinner at the Three Tuns Hotel***

Friday 7th January

08:30-09:00	***Registration; Refreshments & Posters***

Session 7: Continental Margins 2	***Chair: Nick Kusznir***
09:00-09:15	*Shortfalls in Contraction from Submarine Thrust Belts Imply Substantial Lateral Compaction – Insights from the Namibia Continental Margin.* **Rob Butler**
09:15-09:30	*The Utility of Theoretical Forward Modeling Algorithms to aid Cross Section Construction in a Foreland Fold-thrust Belt.* **Steven Clelland*** & R. Butler
09:30-09:45	*Ellesmerian tectonism in the Canadian Arctic Islands: the end of the Franklinian Passive Margin.* **Stephen Rippington**, H. Smyth & R. Scott
09:45-10:00	*An Introduction to Intermediate Crust (IC): its Formation, Epeirogenic Character, and Plate Tectonics Significance* **Miles F. Osmaston**
10:00-10:15	*Discussion*

10:15-10:40	***Refreshments and Posters***

Session 8: Regional Studies	***Chair: Rob Butler***
10:40-10:55	*Shifts in the Intertropical Convergence Zone and the Tectonics and Climate of the India-Eurasia Collision.* H.A. Armstrong & **Mark B. Allen**
10:55-11:10	*Estimating the viscosity of the Tso Morari Gneiss Dome, Western Indian Himalaya.* **Soumyajit Mukherjee** & K. Mulchrone
11:10-11:25	*Formation of the West Siberian Basin by the Decay of a Plume Head.* **Peter J. Holt**, M.B. Allen, J. van Hunen & H-M. Bjørnseth
11:25-11:40	*Regional Magnetic Fabric Study of the Plougastel Formation in the Western Central Armorican Terrane (Brittany, France).* **Tom Haerinck***, T.N. Debacker & M. Sintubin
11:40-11:55	*A Dip Isogon Method for Distinguishing Folded Structures in Sediment and Rock* **Nicholas P.J. Harper***, G.E. Lloyd, & R.E.L. Collier
11:55-12:10	*Eye and Sheath Folds in Turbidite Convolute Lamination: Aberystwyth Grits Group, Wales.* **Nigel H. Woodcock**, H.L.O. McClelland & C. Gladstone

12:10-12:25	Discussion

12:25-13:35	***Lunch & Posters***

Session 9: Salt Tectonics	***Chair: Ian Alsop***
13:35-13:55 (*Keynote*)	*What is a Salt Structure?* **Simon Stewart**
13:55-14:15 (*Keynote*)	*What Drives Salt Flow in the Gulf of Mexico?* **Jean-Pierre Brun*** & X. Fort
14:15-14:30	*Using Polygonal Fault Systems to Reconstruct the State of Stress Associated With Salt Diapirs.* **T. D. Carruthers***, J. A. Cartwright, M. Kristensen & P. Schutjens
14:30-14:45	*Large-scale, Basement-controlled Segmentation of an Evaporite-Detached Fault System: Eastern Margin of the Halten Terrace, Offshore mid-Norway.* **Paul Wilson**, G.M. Elliott, R.L. Gawthorpe, C.A-.L. Jackson, L. Michelsen & I.R. Sharp
14:45-15:00	*Three-dimensional Reconstruction of the Cotiella Extensional Listric Growth Fault System (Southern Pyrenees of Spain).* **Berta López-Mir***, J.A. Muñoz & J. García-Senz
15:00-15:15	*Using Hydrology to Constrain Flow Rates of an Active Salt Extrusion in Iran.* **Christopher J. Talbot**, M. Zarei & E. Raeisi
15:15-15:30	*Discussion*

15:30-15:45	***Refreshments & Posters***

15:45-15:55	***Student Presentation Awards***

Session 10: Hazards & Tectonics 2	***Chair: Ernie Rutter***
15:55-16:15 (*Keynote*)	*Tsaoling and Jiefengershan landslides: two catastrophic landslides triggered by 1999 Taiwan Chi-Chi earthquake as studied by high velocity friction experiments* **Toshihiko Shimamoto**, T. Togo, K. Oohashi, Y. Miyamoto, K. Yano, J-J. Dong & C-T. Lee
16:15-16:30	*The geochemical signature of carbonate-hosted seismogenic faults.* **Nicola De Paola**, G. Chiodini, T. Hirose, C. Cardellini, S. Caliro & T. Shimamoto
16:30-16:45	*Relationship between normal faulting and volcanic activity in the Taranaki backarc Basin, New Zealand.* M. Giba, **John J. Walsh** & A. Nicol
16:45-17:00	*Soft-sediment Deformation Within Slumps Around the Dead Sea Basin.* **G. Ian Alsop** & S. Marco
17:00-17:15	*Relationship between topography and strain-rate in the actively-extending Italian Apennines: evidence of mantle involvement in extension.* J.P. Faure Walker, **Gerald P. Roberts,** P.A. Cowie, I. Papanikolaou, A.M. Michetti, P. Sammonds, M. Wilkinson, K.J.W. McCaffrey & R. Phillips
17:15-17:30	*Discussion*

17:30	***Close Meeting***

Saturday 8th January

"Design of Rock Deformation Apparatus" Workshop

"3-D Model-Building for Structural Consistency" Workshop

Summary

Tuesday

09:00-17:00 "Design of Rock Deformation Apparatus" workshop

Wednesday

13:10-14:30	Session 1: Hazards & Tectonics 1
14:50-16:45	Session 2: Overpressure & Geomechanics
16:45-17:30	Icebreaker
17:30-18:30	Plenary Lecture 1: Diane Moore

Thursday

09:00-10:35	Session 3: Continental Margins 1
11:00-12:45	Session 4: Fault Zone Development & Characteristics
13:45-15:20	Session 5: Energy, Resources & CCS
15:45-17:15	Session 6: Fault Timings & Kinematics
17:15-18:00	Annual General Meeting
18:00-19:00	Plenary Lecture 2: Nick Kusznir
19:30	Conference Dinner at the Three Tuns Hotel

Friday

09:00-10:15	Session 7: Continental Margins 2
10:40-12:25	Session 8: Regional Studies
13:35-15:30	Session 9: Salt Tectonics
15:55-17:30	Session 10: Hazards & Tectonics 2

Saturday

09:00-17:00	"Design of Rock Deformation Apparatus" Workshop
09:00-17:00	"3-D Model-Building for Structural Consistency" Workshop

The Role of Serpentinite in Generating a Weak, Creeping Fault: Evidence From Laboratory and SAFOD Investigations

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Serpentinized ultramafic rocks are closely associated with creeping faults of the San Andreas system in central and northern California. Although serpentinite has been invoked as the cause of the creep, serpentine minerals can exhibit unstable (seismogenic) slip under certain conditions. However, the serpentinite bodies typically are juxtaposed against quartzofeldspathic rocks at depth along these faults. This contrast in rock chemistry can promote fluid-assisted reactions that influence the mechanical properties of these faults, as we demonstrated in a series of triaxial friction experiments conducted under hydrothermal conditions (200-350°C). When lizardite- or antigorite-serpentinite gouges are sheared slowly between blocks of granite or quartzite, their strengths are reduced by as much as 40% to $\mu \approx 0.3$, with the greatest strength reductions at the highest temperatures (temperature weakening) and slowest shearing rates (velocity strengthening, which is inherently stable). For these relatively short experiments (≤14 days) the strength reductions accompanying decreasing velocity were reversible when the rates were increased, and we found textural evidence that some serpentine minerals recrystallized during the experiments. This suggests that the cause of the weakening was a shearing-enhanced, solution-transfer process driven by pore fluids whose chemistry was modified by interaction with the quartzofeldspathic wall rocks. Solution-transfer processes involving dissolution and reprecipitation of serpentine have been described in serpentinite-bearing faults in California, and they may lead to aseismic slip and weakening in the short term in such faults. Over time, however, chemical diffusion between ultramafic and quartzose rocks should lead to the formation of a new mineral assemblage that will eventually control the mechanical behavior of the faults. Evidence of such reactions was seen in the 14-day experiments, in which minor amounts of Mg-rich, saponitic smectite clay grew metastably on shear surfaces. The two actively creeping traces identified in the SAFOD (San Andreas Fault Observatory at Depth) scientific drillhole across the San Andreas Fault near Parkfield, California may represent natural examples of the longer experiments. Both traces are narrow zones of fault gouge that consist of porphyroclasts of serpentinite and sedimentary rock dispersed in a foliated matrix of saponite ($\mu < 0.1$) and some corrensite, a regularly interlayered chlorite-smectite clay. Porphyroclasts of all types are variably altered to the same Mg-rich clays as the gouge matrix. The two creeping strands are interpreted to be the product of shear-enhanced metasomatic reactions between serpentinite and the adjacent sedimentary rocks.

Global Exploration of Rifted Continental Margins and Micro-continents: Mapping Crustal Thickness and Ocean-Continent Transition Using Satellite Gravity Inversion

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The exploration and mapping of rifted continental margins and ocean basin development is the focus of much current attention motivated by hydrocarbon exploration, territorial claims and geo-dynamic research. Satellite gravity anomaly inversion incorporating a lithosphere thermal gravity anomaly correction has been used to determine Moho depth, crustal thickness and continental lithosphere thinning factor for oceans and continental margins and to map ocean-continent transition location and micro-continent distribution. Using a new gravity anomaly inversion method which incorporates a lithosphere thermal gravity anomaly correction, we have produced the first comprehensive maps of crustal thickness and oceanic lithosphere distribution for the world's oceans including the Arctic. Continental lithosphere thinning factors and crustal thickness from gravity inversion provide independent predictions of ocean-continent transition location which is important in deep-water hydrocarbon exploration. Superposition of illuminated satellite gravity data onto crustal thickness maps from gravity inversion provides improved determination of pre-breakup rifted margin conjugacy and sea-floor spreading trajectory. Crustal thickness maps from gravity inversion, restored to early post-breakup times using plate reconstruction rotation poles, show the geometry and segmentation of breakup rifting and the location of failed breakup basins and micro-continents. The abundance of anomalously thick crust within oceanic regions, interpreted as micro-continents and often associated with multi-phase volcanism, suggest that the development of the world's oceans has a more complex history than usually shown by most plate reconstructions. Input data used in the gravity inversion is globally available satellite gravity, digital bathymetry and sediment thickness. Gravity inversion to determine Moho depth and crustal thickness variation is carried out in the 3D spectral domain and incorporates a lithosphere thermal gravity anomaly correction for both oceanic and continental margin lithosphere. Failure to incorporate a lithosphere thermal gravity anomaly correction gives an over-estimate of crustal thickness predicted by gravity inversion. A correction is made for crustal volcanic addition due to decompression melting during breakup and sea-floor spreading.

Crustal Velocity Field from InSAR and GPS Reveals Internal Deformation of Western Tibet

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A fundamental question in continental tectonics is the degree to which strain is focused on major faults. Existing deformation data from the largest deforming area on the planet, the collision zone between India and Asia, are insufficiently dense to answer this question. Satellite radar interferometry is a tool that enables surface deformation to be measured in remote parts of the world with no requirement for ground-based instrumentation. By using multiple interferograms acquired over extended time periods, deformation rates can be recovered with a precision comparable to that of GPS. We have combined 265 interferograms formed from 166 radar images with sparse GPS data to constrain a high-resolution velocity field covering ~200,000 km^2 of western Tibet. The results show that strain is concentrated in the interior of the plateau, away from the major faults. This is incompatible with block models of continental tectonics, but is consistent with continuum models modified by the short-term influence of the earthquake cycle. Block models have been used to argue that the majority of seismic hazard in the continents is localized around the block boundaries. The broad distribution of strain that we observe is consistent with recent findings from the Aegean, and suggests that significant seismic hazard in the continents exists away from major mapped faults.

Crustal Deformation of the Central Tibetan Plateau Measured Using InSAR

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Contrasting models have been proposed to describe the ongoing deformation of the Tibetan plateau as a result of the India-Asia collision. One extreme involves rotations of rigid elastic blocks bounded by major faults which penetrate the entire lithosphere. This description implies relatively high slip rates on block bounding faults and distinct narrow shear zones. In the alternative extreme, the bulk continental lithosphere is considered to deform continuously as a viscous fluid. Deformation in the brittle upper crust is driven by tractions imparted on its base from the viscous layer beneath, and distributed on a large number of shallow faults throughout the deforming zone. As a result, slip rates on faults are lower, and their straining zones merge together. There are very few GPS measurements of surface velocity in the plateau interior, therefore it has been difficult to verify either of the proposed models. Interferometric synthetic aperture radar (InSAR) has proved to be a powerful technique which dramatically increases the spatial density of velocity measurements. We use this technique on a network of 32 Envisat ASAR images acquired between 2003 and 2009 on descending track 176 in the centre of Tibet. The swath length of ~1100 km spans the majority of the uplifted plateau and covers three major east-west trending shear zones; the Kunlun fault, Jiali shear zone, and the westward continuation of the Xianshuihe fault. We use a multi-interferogram network algorithm to determine the orbital error and the topographically correlated atmospheric phase delay. We remove these contributions and solve for the deformation rate at each pixel in a least squares inversion. The large along-track extent of the rate map enables recovery of tectonic signals at the hundred kilometre scale using this method. However, we are also interested in the longer wavelength signal across the whole plateau. We therefore adjust the rate map using an initial velocity model constructed from published GPS data. The resulting rate map shows the distribution of strain across the broad deforming zone of the Tibetan Plateau during the interseismic period. We use a velocity profile through the rate map to test the proposed deformation models and find that neither published elastic block models or numerical viscous models can recreate the velocity field measured using InSAR.

The Active Deformation Front of the Gobi Altai Transpressional Orogen, Mongolia: Insights Into Processes of Continental Interior Reactivation

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Young and actively forming intracontinental, intraplate oblique deformation belts like the Gobi Altai in Mongolia are characterised by diffuse and complexly linked transpressional fault systems that generate a basin and range topography. In the northeasternmost Gobi Altai in southern Mongolia, the orogen is growing northwards and eastwards and provides an excellent opportunity to study the earliest stages of crustal rejuvenation and mountain building in a continental plate interior. Detailed remote sensing analysis and structural fieldwork indicate that the orogen is growing by: 1) rift inversion, 2) regional anticline growth due to either normal fault inversion or new thrust fault propagation, 3) restraining bend growth along-strike and perpendicular to strike, 4) thrust displacements along steep oblique-slip faults, and 5) basement arching. In the subdued landscapes along the margins of the orogen, the first evidence for active transpressional deformation is revealed by deflected drainages, fluvial incision through regionally arched terrain, migrating fluvial fan deposition sites, and long wavelength subtle fold development (wavelengths = 20kms+, limb dips less than 3^{o}). Range-bounding thrusts locally reactivate Cretaceous normal faults whereas linking strike-slip faults cross-cut older faults and fabrics. The evolving orogen is spatially constrained by more rigid Precambrian basement to the north, but is free to grow eastwards into a mechanically weaker Palaeozoic terrain collage consistent with GPS data that indicate that the Gobi Altai crust is moving eastwards between 3-5mm/yr. It is likely that reactivation of northern Gobi Altai crust was facilitated by Cretaceous crustal thinning and sustained thermal weakening of the lower crust and lithospheric mantle due to 160 my of episodic volcanism in the region since the Late Jurassic.

Tectonic Evolution and Present-day Kinematics of the Palu-Koro Fault, Eastern Indonesia

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The Palu-Koro Fault of Sulawesi Island is a major strike-slip fault in Eastern Indonesia, a region of intense active deformation. It has a slip rate between about 32-45 mm/yr and left-lateral displacement of the order of 200 km. Palaeomagnetic evidence, plate tectonic reconstructions and the presence of exhumed Pliocene granites along its length all indicate that the fault was initiated no earlier than about 5 Ma. Stream offsets, deformed Quaternary fans, GPS motions and significant historical earthquakes show that it has remained active to the present day.

Basic hypabyssal rocks that are weakly, or not metamorphosed crop out west of the NNW-trending fault zone. Close to the fault, medium to high grade metamorphic rocks, including mylonitic amphibolites and granulites, and garnet peridotites crop out. East of the fault a broad metamorphic belt is dominated by low to medium grade metasediments in the north, and high grade gneissic rocks in the south and far east. Ductile deformation fabrics in many of these rocks show evidence of widespread mid-crustal flow, some of which may pre-date the Palu-Koro Fault, and some of which may record the rocks' exhumation.

Previous models have shown the Palu-Koro Fault as simply accommodating rotation of rigid blocks driven by Australia-Eurasia collision. We propose that it is part of more complex deformation linked to subduction roll-back in the Celebes Sea, and associated with exhumation mechanisms such as metamorphic core complexes and other extension-driven features, that may have analogues in other young orogens.

The Mechanical Implications of High Fluid Pressure Reservoirs at the Base of Seismogenic Zones: Observations and Modeling

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Ubiquitous evidence suggests that large reservoirs of over-pressured fluids reside at the base of seismogenic zones, but little has been studied as to the hydromechanical effects of such fluids on the preparatory process of large earthquakes. Episodic tremor and slow slip earthquakes call for lithostatically pressured fluids along the down-dip extension of mega-thrust earthquakes, and recent evidence from a series of earthquakes point to trapped over-pressured pockets in the crust. If such high pressure reservoirs exist, then they impart a significant mechanical influence on the nucleation phase of earthquakes, including pore-elastic effects and the invasion of high pressure fluids into the source region. Modeling these processes requires that fracture networks are allowed to evolve in response to the prevailing regional stress field, local stress perturbations, and fluid flow within the evolving networks. The underlying physics is numerically challenging because of the time-scales involved; from the elastic wave speed of crack growth to a pressure-dependent (non-linear) diffusion model for fluid flow. Changes in fluid pressure introduce stresses in the porous solid, which may lead to either hydro-fracture or shear fracture. Seepage forces related to pore pressure gradients may also promote de-localized crack formation. In this talk, I will present the evidence for overpressured fluids at depth, and how these processes can be modeled to gain deeper insight into the complex hydromechanical feedbacks of the earthquake process.

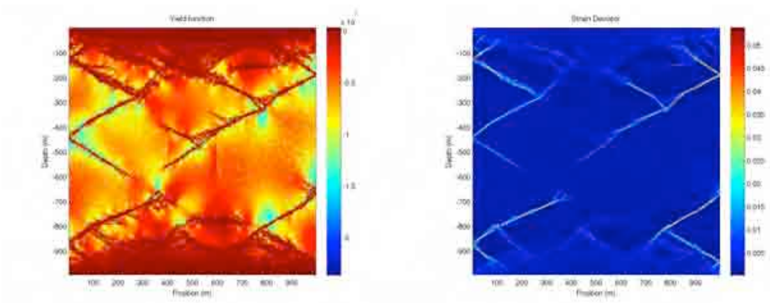

Figure 1. Numerical modeling results of fracture evolution in a pore-elastic plastic rheology. The yield function shows model regions that have failed either in tension or shear, and the deviatoric strain is used a proxy for fracture aperture (permeability) in a coupled hydromechanical model.

Pore Pressure – Stress Coupling: Evidence from Deep Boreholes

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Porelasticity results in a coupling between the pore fluid pressure within buried rocks and the horizontal compressive stress. Attempts to quantify the magnitude of the coupling have led to reported coupling ratio values in the region 0.5 to 0.8. Most previous reported values have used a minimum (horizontal) stress estimated from a regional compilation of leak-off test (LOT) data.

We present a new approach to determination the coupling ratio for 3 basins in NW Europe which experience a range of excess pore pressures at depth. The method uses only those LOT data in wells for which the corresponding excess pressure is well defined, i.e. from wells in which there are sufficient direct pore pressure measurements within reservoir intervals to determine well constrained water gradients, and hence reliable values of overpressure. Relationships between fracture pressure and depth and locally derived lithostatic stress gradients have been developed as part of the work flow. The coupling ratio is then determined from the residual required to match the prediction based solely on depth and lithostatic stress and actual LOT values for the ranges of overpressures.

The coupling values we determine for the North Sea Central Graben, mid-Norway and North Viking Graben basin areas are 0.35, 0.28 and 0.3 respectively, well below previously reported values. Further these values are much lower than coupling ratio estimates for horizontal stress reduction during reservoir depletion. We will provide supporting data from other deep boreholes in deltaic and sub-salt settings in which the same magnitude is observed.

We are illustrating a new approach to quantification of pore pressure-stress coupling, and explore the reasons why the coupling ratio values are lower than previous published estimates. These pore pressure stress coupling values are now embedded in region-specific algorithms for the prediction of fracture gradients, and form the basis for analysis of seal breach risking in these areas.

Development of a Fluid Flow Pipe Triggered by Lateral Pressure Transfer on a Sub-Circular Fold, Deepwater Niger Delta

Amélie M Leduc*[1], R J Davies[1], R E Swarbrick[2], A L Densmore[3] & J Imber[1].
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Deformation in passive margins gravitational detachment systems is generally divided into three to four main structural domains including a proximal extension zone, an intermediate translation and diapiric zone and a downdip compression zone. However recent acquisition of three-dimensional industry seismic data provide higher resolution evidence allowing a more detailed interpretation of structures commonly termed shale diapirs.

We present a kilometre-scale radius sub-circular detachment fold in a gravity detachment system primed by overpressure, deepwater western Niger Delta. A fluid flow pipe, c. 650 m in diameter, is found at its crest. A combination of processes is proposed to explain the development of the fold and the pipe. The fold growth is contemporaneous to the development of a growth fault in the north and a right-lateral strike-slip fault in the west of the study area. The Pliocene (?) folding event triggered lateral pressure transfer by tilting of a late Miocene aquifer. Expulsion of overpressured fluids is caused by this transfer of pressure in a shallow reservoir (1800 m below the seabed in a c. 6000 m-thick sedimentary succession), showing that the source of overpressured fluids does not need to be as deep as the strata within which gravitational detachment occurs.

Metamorphic fluid overpressures: experiments and a numerical model

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There is no doubt that fluid pressure is a prime influence on brittle failure and consequently we need to understand how fluid pressure evolves in the Earth. Fluids are produced during dehydration reactions and the elevated fluid pressure resulting may promote brittle failure. This has been invoked to explain, for example, intermediate depth seismicity in subduction zones.

Most dehydration reactions involve a net volume increase; hence in confined conditions overpressure develops unless the fluid can drain away. Thus, porosity and permeability development are key processes. However, what controls dehydration reaction rate? Because they involve volume change, dehydration reactions are sensitive to pressure. But in general, a porous rock is under confining pressure different to fluid pressure. Which of those pressures controls the reaction, or do they both? This is a key question because the evolving pressures will *feedback* on the reaction.

We have run an extensive set of experiments on gypsum dehydration (to bassanite) to address key questions relating to fluid pressure development and, in parallel, have developed a numerical model for dehydration. Two important results to date are:

1. Experiments show that the rate of gypsum dehydration is strongly influenced by pore fluid pressure and not by confining pressure. We call this “protected growth”, because it means that, even as the bassanite becomes the dominant load supporting phase, the confining pressure it supports is not influencing the thermodynamics of the reaction.

2. Experiments and the model both show that under some conditions a reaction *front* develops, separating unaltered gypsum from substantially reacted regions, and marking also a front of fluid pressure. The reasons for development, and the significance, of such fronts will be discussed.

Low Temperature Creep in Carbonate Materials: Effect of Reactive Fluids and Transient Deformations

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In the rocks of the Earth's upper crust (0-15 km depth), it is generally considered that the rheology is elastic. However, in specific cases, deformation involves slow creep or other viscous-like behaviors. This is the case in sedimentary basins, where sediments slowly compact by porosity reduction. This also occurs in active fault zones or landslide sliding zones, where it is now widely observed that elastic behavior (i.e. earthquakes, dynamic ruptures) interact with creep processes (slow earthquakes, afterslip, creep).

Because of the low temperature conditions, these creep processes of crystalline rocks are not related to dislocation motions (i. e. crystalline plasticity), but are due to interactions between mechanical processes, such as grain sliding, microcracks propagation, and chemical processes such as dissolution, precipitation of minerals. Together these processes may induce large scale, pervasive and permanent strain.

These processes are slow, and controlled be many parameters such as stress, temperature, grains size, and fluid chemistry. Therefore laboratory experiments are needed to characterize the kinetics of deformation. I will present here a set of new experiments performed on three kinds of carbonate rock materials: single grains (to isolate processes), non-cohesive mineral aggregates (to obtain a collective behavior), and cohesive rocks. These experiments allows separating two main deformation processes: dissolution-precipitation under non-hydrostatic stress (i.e. also called pressure solution creep) and slow crack propagation (i.e. also called subcritical crack growth or stress corrosion). These experiments are difficult to realize for two main reasons. On the one hand, the processes are very slow and long-term, well-controlled experiments are needed. On the other hand, transient deformation processes are at work and may control short-term deformation processes.

Some applications to porosity reduction, healing of active faults after an earthquake, and carbon geological sequestration will be discussed. The goal is there to propose constitutive laws for creep processes in the Earth's upper crust.

Clast-Cortex Grains in Nature and Experiment: Fossil Earthquakes in Limestone?

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Many destructive earthquakes in central Italy (e.g. L'Aquila Mw 6.3, 6 April 2009), and in other areas worldwide, nucleate within and rupture through limestones. During individual earthquakes a majority of fault displacement is accommodated by thin principal slip zones (PSZs). We present microstructural observations of the PSZs of seismically-active normal faults that cut limestones in central Italy, and compare these PSZs to experiments on layers of simulated calcite gouge using a recently-installed rotary-shear apparatus (**SHIVA**, **S**low-to-**Hi**gh **V**elocity **A**pparatus) at INGV, Rome. Geological constraints indicate that the natural PSZs are exhumed from <2km depth and <100°C, whilst SEM and XRD observations suggest they are composed of c. 100% calcite. The PSZs contain a 2-10 mm thick layer of ultracataclasite. Peculiar rounded grains up to c. 1mm in diameter consisting of a central (often angular) clast surrounded by a laminated outer cortex of ultra-fine grained calcite are found in the ultracataclasite layer. These *clast-cortex grains* resemble other types of accretionary grain that are thought to form during fluidization processes, including *accretionary lapilli* within pyroclastic surges, and *armoured carbonate grains* from the basal decollements of mega-landslides. We suggest that the clast-cortex grains within the limestone slip zones formed during fluidization of the ultracataclasite at high strain rates during earthquake rupture. To test this idea, we have initiated a series of rotary-shear experiments using 3 mm-thick layers of water-saturated calcite gouge (<125 μm) deformed at a constant normal stress of 1.5 MPa and slip velocities between 1 mm/s and 6.5 m/s. At slip velocities <10 cm/s the calcite gouge has a steady-state frictional strength of 0.6-0.7 and is dominated by cataclastic fabrics that are cross-cut by well-organized Y- and R'-type Riedel shears. At slip velocities >1 m/s (i.e. seismic slip velocities), the calcite gouge shows an initial peak friction of 0.5-0.7 followed by a rapid decay in friction (in <1m of slip) to a steady-state value of 0.1-0.3. SEM observations show a localized zone of deformation <300 μm thick, inside of which relatively large clasts of calcite are wrapped by an outer cortex of much finer-grained material, and closely resemble simple examples of natural clast-cortex grains. We suggest that clast-cortex grains may be a diagnostic microstructure of seismic slip in limestones. Future experiments will cover a wider range of slip velocities (1 μm/s – 6.5 m/s) and normal stresses (1-10 MPa) and will be used to constrain the velocity/stress regime in which clast-cortex grains form, and to investigate their microstructural evolution with increasing slip.

Extreme Crustal Thinning and Mantle Exhumation at Deep-Water Rifted Margins: the Lesson From the Iberia-Newfoundland and Alpine Tethys Margins and Applications to the pre-Salt Basins of the S-Atlantic

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Research into the formation of passive rifted margins is incontestably undergoing a paradigm shift. The discovery of exhumed mantle and hyper-extended crust overlain by shallow marine sediments is proving fundamental in defining the controls and processes that thin continental lithosphere, lead to continental break-up and formation of oceanic basins. At present, little is known about the depositional environments, sedimentary facies, the kinematics and age of structures, or the subsidence and thermal history of syn-rift sediments of deep-water rifted margins. In my presentation I will therefore review the key observations made along the Iberia-Newfoundland and Alpine Tethys rifted margins and will try to show how they may impact our thinking and understanding of the pre-salt basins of the S-Atlantic.

The study on the Iberia-Newfoundland rifted margins showed that the transition from continental to oceanic crusts does not represent a sharp boundary, but is formed by an up to 160 km wide zone of exhumed sub-continental mantle. This observation questions the existence of a sharp and well-defined ocean-continent boundary at magma-poor rifted margins and asks about the validity of the breakup unconformity and nature and significance of magnetic anomalies in ocean continent transitions.

Mapping of rift structures and depositional systems of the ancient Alpine Tethys margins enabled to identify lithologies and structures similar to those drilled off Iberia. The most prominent structures observed in the Alps are a set of detachment faults. These structures can be traced from relatively unextended continental crust across the distal margin and ocean-continent transition towards embryonic oceanic crust. These faults are far more complex as proposed by the Wernicke model. Detachment faults interact with decollements in ductile layers and only when the crust is thinned to less than 10 km and is completely brittle, detachment faults can cut from the surface into mantle and exhume the latter at the seafloor. Fluids are intimately linked with this process, controlling rheological and thermal evolution.

The lesson from the Iberia-Newfoundland and Alpine Tethys rift systems might not explain the whole S-Atlantic, however, it may help to re-evaluate and rethink some to the concepts, the terminology and the processes that were (are) used to describe rifting and continental breakup along their margins.

The Deep Structure of the Porcupine Basin: Comparison with the W. Iberian Rifted Margin

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The Porcupine Basin is known to have accumulated very large amounts of extensional strain, with estimates calculated from subsidence data suggesting the lithosphere has a stretching factor (β_{WL}) greater than 6 at its centre. Preliminary interpretations made using ION-GXT's deep penetration 2-D (PSDM) seismic data - acquired as part of its NE AtlanticSPAN™ – have allowed for calculation of the crustal stretching factor (β_C) for the Porcupine Basin based on measurements of crustal thickness variations across each seismic line.

The data shows clearly the extreme extension which has occurred in the South Porcupine Basin and demonstrates an increase in extensional strain southwards toward the Seabight Basin. β_C ranges from c. 13 (locally) at the Porcupine Arch to infinity further south where crustal separation and exhumation of serpentinised mantle has occurred. As such, there are strong parallels which can be drawn between the Porcupine Basin and Magma-Poor Rifted Margins (MPRMs) such as the W. Iberian Margin, with many observed structures being common to both.

Here, we present some of the classic MPRM characteristics the Porcupine Basin displays via comparisons between the Porcupine Basin data and published seismic data from the W. Iberian Margin, such as; low volumes of syn-rift magmatism, serpentinite detachments, "peridotite" ridges, and a zone of exhumed continental-mantle/ (proto-) continent-ocean transition. We also present a new map detailing crustal stretching factors for the Porcupine Basin, and suggest potential mechanisms for accommodating the extreme extension observed.

We suggest that the Porcupine Basin be classified as a "failed" magma-poor rifted margin as crustal separation has occurred to the south but sea-floor spreading had not initiated by the cessation of extension.

Evolution of the Rockall Trough: A Numerical Modelling Approach

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The Rockall Trough is one of the largest, relatively unexplored basins forming the North-East Atlantic passive margin and many aspects regarding the evolution of this basin remain unresolved. In part, this is due to the Palaeocene lavas associated with the opening of the North Atlantic Margin and the Icelandic Hotspot which inhibit high resolution imaging of the underlying sediments and basement structure.

The aim of this study is to apply numerical, lithosphere-scale models to the Rockall Trough in order to gain insights into the complex evolution of this passive margin basin. Model cross-sections of the basin have been produced in order to determine the interplay of geological, rheological and geodynamic processes that have controlled the evolution of the Rockall Basin. These models are used to test different hypotheses regarding the timing and nature of extensional and compressional events as well as the influence of thermal anomalies, and spatial and temporal variations in lithospheric rheology. Initial results demonstrate the importance of accurate controls on palaeobathymetry and the need to realistically account for varying basin fill sequences during different stages of the Rockall Trough's evolution.

An analysis of available subsurface data has been undertaken to quantify the amount of stretching that has occurred during the evolution of the Rockall Trough. Additionally, analyses of composite well data have been used to generate subsidence curves for the basin, which highlight key episodes of anomalous subsidence. The main event highlighted by the subsidence curves is a major deepening event which occurred during the Eocene. These curves are compared to modelled subsidence curves in order to test the validity of the structural and geodynamic scenarios that have been modelled. Further validation of the model results has been carried out by comparing regional gravitational anomaly data with theoretical gravity anomalies calculated from the model profiles.

Model results show the relative importance of different basin-controlling and geodynamic parameters, and how they affect the basin's evolution. Variations in rheological properties and lithospheric strength are shown to account for the main differences in evolution between the North and South Rockall Trough. Future work aims to investigate possible mechanisms, such as regional flexing of the lithosphere, mantle flow, etc, that may explain the major deepening event identified in the Eocene.

Controls on Passive Margin Evolution: A case study of the Santos Basin, Southeastern Brazil

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Passive margins are thought, since early in the development of plate tectonic theory, to be strongly influenced by pre-existing structures. The nature of this influence is not well understood, and hypotheses have ranged from small scale basement fabric and fault reactivation to large-scale influence by major crustal structures and mantle fabrics. In order to understand the evolution of passive margin basins, it is crucial to understand what the controls on margin formation are, and how they affect the development of brittle structures in the offshore basins. The Santos basin is one such passive margin basin, with hydrocarbon discoveries such as the giant Tupi oil field hosted in syn-rift plays. The basin is thought to be underlain by the Ribeira mobile belt, formed during the Neoproterozoic Brasiliano (or pan-African) orogeny. Brittle structures in the offshore basin are thought to have been influenced by pre-existing Ribeira belt structures. The onshore region bordering the Santos basin, in Rio de Janeiro, Sao Paulo, Paraná and Santa Catarina States offers an opportunity to test this hypothesis, and to study the controls on evolution of oblique passive margin segments. Field study of outcrops across the margin has shown that while basement fabrics in the onshore region are strongly parallel to brittle structures in map view, they display more variation in the third dimension (dip). We highlight the importance of 3 major early Cretaceous dyke swarms (the NE – SW Serra do Mar, NW – SE Ponta Grossa, and the NNE –SSW Florianopolis swarms), and faults and fractures identified as having formed before, during and after dyke intrusion. 3 separate regions of fracturing, each associated with separate dyke swarms are identified, and the similarity between the orientations of these faults and fractures, and dyke orientations, suggest a similar control on both igneous intrusion and faulting, and highlighting the interplay between tectonics and magmatism during the formation of this passive margin. The 3 dyke swarms have been hypothesized as being a triple junction – suggesting their development is a response to larger scale, tectonic stresses. Whilst these field data show local reactivation, the consistent structural trends in the 3 main dyke swarms, compared with a heterogeneous basement in terms of both composition and structure suggests a larger scale control than direct basement reactivation. We propose that the control on the orientation of syn-rift structures in the Santos basin, and the onshore region, was unlikely to have been local scale basement heterogeneity, and was more likely to have been the interplay between large-scale tectonic stresses and possibly the influence of orogenic mantle fabrics and/or mobile belt-scale structures formed during the Brasiliano orogeny.

Role of Irregular Plate Margins in the Neoproterozoic-Cambrian Tectonic Evolution of the Brasília Belt, Central Brazil

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The Brasília, Araguaia and Paraguay Belts, components of the N-trending Tocantins Province, stretch between the Amazon and São Francisco cratons (formerly paleocontinents), occur partially covered by Phanerozoic sedimentary rocks of the Paraná and Parnaíba basins. The segment of continental lithosphere existing underneath the Paraná basin is known as the Paraná block. The three belts record collision tectonics in the Neoproterozoic-Cambrian tectonic evolution of central Brazil. The Brasília Belt (**BB**) is comprises three lithotectonic domains (a magmatic arc, an Internal Zone and an External Zone) longitudinal to the western margin of the São Francisco craton. At the latitude of the Brasília Dome, an elliptical and N-trending structural window situated in the centre of the External Zone, the belt bends gradually and becomes an orocline divided into a NE-trending northern segment and a SE-trending southern segment.

The results of detailed structural works in the last two decades, crowned by more recent structural studies around the Brasília Dome, allow to show (*1*) a structural evolution in the northern segment due to D_1-D_2 and D_{3N} ductile events of shortening, all implying WNW-ESE direction of movement; (*2*) in the southern segment, D_1-D_2 events still record WNW-ESE movement, but the third phase records contraction in the SW-NE direction (D_{3S}); and (*3*) D_{3S} contraction overprints D_1-D_2-D_{3N} in an area slightly south of the orocline axis and situated south of and close to the southwestern margin of the dome.

Coupled with the results of other´s geological research in the last two decades, the structural data across the belt allow understanding that: *(a)* D_1-D_2 records ~750-640Ma propagation of nappes toward ESE, onto the São Francisco paleocontinent, consequence of arc-paleocontinent amalgamation, diachronous from N to S across the **BB**; (*b*) the ~640-590 Ma-old contraction, D_{3N}, marks the final evolution of the Amazon-São Francisco collision, whereas the ~630-590 Ma-old contraction, D_{3S}, records the Paraná-São Francisco collision and orocline formation, both compatible with the ~620-540 Ma opening-infilling of the basin precursor or the Paraguay Belt and its continuation in the younger western part of the Araguaia Belt; (c) final squeezing of the Paraná block between the two paleocontinents resulted in 550-510 Ma-old contraction, also SW-NE, in the very southern end of the BB; and (*d*) irregular continental margins controlled the evolution of the Amazon-São Francisco collision and resulted in the Neoproterozoic-Cambrian evolution of central Brazil.

3D Modeling of Fracture Density and Connectivity Within Faulted Chalk Reservoirs – A Case Study From Flamborough Head, UK

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The anisotropic distribution of fracture density and connectivity in 3D across a fault zone can exert a strong control on fluid flow. However, fracture density and connectivity values are usually estimated quantitatively using 1D and 2D fracture datasets, which do not take into account the aspect ratio (length of the fracture along dip/length of the fracture along strike) of the individual fractures.

In this study fracture datasets derived from interpretation of LiDAR images were used to model the anisotropic distribution of fracture density and connectivity in 3D across a fault zone developed in a chalk reservoir. We modeled a range of fracture aspect ratios in order to test the control exerted by fracture dimensions on connectivity and its spatial variation. Finally, results obtained from 2D and 3D dataset analyses were compared in order to give a best-fit estimate on the real aspect ratio of the fractures.

The study focused on a complex normal fault with a total displacement of about 25 m, developed within low-porosity, fine-grained Upper Cretaceous chalk which is well exposed in the Flamborough Head area (UK). The fault zone is comprised of two ENE-WSW-striking fault cores (FC), 4-5 m apart. Each of the cores is up to 2 m thick, and made of fault breccias with intense carbonate veining. The damage zones, developed on both side of the cores contain thick (up to 15 cm) veins displaying large (5-6 mm) grain size crystals.

Detailed field-based structural observations and mesoscale data collection along 1D-, and 2D fault orthogonal transects were integrated with LiDAR data. The 1D- and 2D analyses showed that fracture density and connectivity in the damage zones are two times higher than in the cores. Within the damage zone a high fracture density and connectivity domain (ICDZ) has been identified next to the core and a high fracture density, low connectivity domain (WCDZ) located further away from the core.

Based on the LiDAR data, fractures of the fault zone were modeled in 3D using 5 different aspect ratios ranging from 1/1 to 1/8. Increasing the elongation of the modeled fractures caused higher fracture density and a greater degree of connectivity. The observed WCDZ and the ICDZ domains gave closest matchwith the lowest aspect ratios (1/3 to1/8). The 3D model results that fits best with the observed fracture density and connectivity values from the 1D and 2D analyses are those with the 1/5 aspect ratio. This best-fit aspect ratio can then be used in fluid flow models to better define the fluid transmissibility across the fault zone.

Development of a Multi-scale Fracture System Throughout the Cambro-Ordovician Sedimentary Succession in Southwestern Jordan

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The highly fractured Cambro-Ordovician sedimentary succession in Jordan consists of marine fines, overlain by deltaic deposits (~100 m combined thickness), culminating in ~500 m of massive to cross-bedded fluvial sandstones. Multiple phases of tectonic stresses have generated and reactivated the extensive fracture system. A data set is acquired from high-resolution satellite imagery and field data, consisting of more than 27,000 individual fractures, that enables the quantification of the geometry and spatial characteristics of the multi-scale fracture network. A hierarchical structure has been developed that assembles fractures into orders of similar characteristic sizes: from 1st order fractures representing the large (seismic) scale discontinuities to 3rd order fractures observed in the field.

Two dominant fracture sets (N65° and N145°) and two minor sets (N40° and N120°) are identified for all fracture orders. 1st and 2nd order length distributions, log-normal and power-law respectively, are only influenced by major lithofacies boundaries and possibly represent different boundary conditions for fracture development. A nested joint organization is recognized for the 3rd order fractures in the stratified base of the succession. Spacing values near or above fracture saturation are common for small fractures (height < 1 m) in the stratified lithofacies, while these are often below the fracture saturation for taller fractures throughout the studied sequence (closely spaced fractures). Fracture corridors occur frequently throughout the study area. These km-long zones bounded by higher order fractures exhibit fracture densities that are more than 3 times higher than the average values in the surrounding rocks.

A multi-scale fracture model is proposed that characterizes the observed fracture network throughout the entire Cambro-Ordovician sedimentary succession and elaborates on the mechanisms that might have caused the interaction of stresses and heterogeneous lithofacies on different scales. The concept of fracture domains - areas bounded by 1st order fractures - is developed as a tool to quantify and constrain spatial variation of fracture characteristics. These models form the basis for numerical modeling experiments in the next phase of this project.

Characterising Fracture Systems on the Isle of Lewis: An Onshore Analogue for the Clair Field

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The Clair oil field lies offshore from western Shetland and is estimated to contain over 4 billion bbl. The basement here is composed of Lewisian-like rocks that are overlain by a reservoir of Devonian-Carboniferous sandstones and conglomerates of the Clair Group. Reservoir performance indicates that fractured basement rocks play a significant role in the resource development of the Clair field. Basement within the Clair field lies in the footwalls of major normal faults with Mesozoic age displacements whose characteristics are important to understand in order to gain a more accurate insight into fracture network behavior. Consequently it is important to characterise and understand the fracture networks within the basement and, in so doing, determine a connected volume within the reservoir. The Hebridean Islands lie in blocks that were upfaulted during the Mesozoic in analogous structural situations to the Clair Field. Lineament analysis reveals significant variation between postulated terranes, and comparison between the cover and basement lineaments indicates the presence of older pre-Mesozoic structures that are dominant within the basement. Fieldwork is hence required to determine the impact of Mesozoic faulting within the Lewisian.

On the west coast of Lewis the Permo-Triassic Stornoway Formation is a synrift conglomeratic unit faulted against Lewisian Complex basement and the Outer Hebrides Fault Zone. Analysis of fractures within the Stornoway Formation reveals at least three sets of cross-cutting faults. Associated fault rocks are typically red-brown and associated with carbonate cements and veins, with varying degrees of induration. These same fault rocks and carbonate cements can be used to identify Mesozoic faulting within the Lewisian Complex of the region and it is clear that many of these faults have formed very significant fluid flow conduits synchronous with and subsequent to faulting. The Mesozoic faults, including the main bounding faults of the Stornoway Formation exposed on Lewis, have a strong tendency to reactivate local foliation within the basement. The relationship between pre-existing fractures within the basement is also investigated. Mesozoic reactivation and fluid flow along older fractures plays an important role within the basement.

Predicting the Internal Structure of Fault Zones in Igneous Rocks and its Effect on Along-Fault Fluid Flow

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Interest in the architecture of fault zones in sedimentary rocks has intensified over recent years, in particular because faults play an important role in hydrocarbon migration. Although most hydrocarbon reservoirs are found in sedimentary basins there are also hydrocarbon plays within igneous rocks, with some 30% of these contained in basalt. Additionally, basalt is a potential carbon dioxide storage option, as chemical reactions between CO_2 and mafic minerals can cause carbonates to precipitate, locking CO_2 in a solid phase. To understand and predict how fluid moves through a fault zone, it is necessary to understand the processes and the mechanics involved in faulting. These processes include initiation and growth of a fault, generation of fault rocks within the fault zone, and subsequent evolution of fault rocks with increased slip. It is therefore key to study the internal structure of faults in igneous rocks to be able to understand the controls on, and make predictions of, fluid flow throughout the fault system.

Whilst extensive studies have been carried out on faults in sedimentary rocks and some work has been done on faults in granites and gneisses, little work has focused on the evolution of faults in extrusive igneous rocks, including basalt. Our study therefore focuses on faults in basalt, with the aim to describe the processes through which fault rocks are generated, and how they evolve through time. Field work in Scotland and Iceland has provided data for a new model of fault evolution in basalt, and we present our preliminary results here. As a fault grows by fracture linkage and propagation, fracture-bound breccia zones are formed. With increasing movement, fractures develop into slip surfaces, and fracture bound breccia zones are further deformed into micro breccias and cataclasites forming the core material. Gouge formation is dependant on host rock variation (i.e. weaker mechanical units and sedimentary horizons) which can control fault width. Micro- and meso-scale fracturing in the footwall and hanging wall creates coarse protobreccia which later is consumed by the fault. The damage zone is dominated by fractures with no large component of shear. This evolution is documented from faults of cm- to m- scaled fault zones, further work aims to examine faults with larger offsets.

The Origin and Nature of Cenozoic Faults and Dyke Swarms in North East Ireland

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The Cenozoic tectonics of North West Europe is generally attributed to a combination of three major controls: Alpine compression, mantle plume-related uplift and North Atlantic opening. North East Ireland hosts extensive exposures of Paleogene rocks of the North Atlantic Igneous Province and in combination with a number of high resolution geophysical data sets, provides a firm basis for considering the contribution of each factor.

Evidence derived from analysis of the Tellus aeromagnetic dataset suggests that the principal Paleogene-Oligocene structures of North East Ireland are conjugate strike-slip faults and, apparently synchronous, regional dyke swarms.

Whilst Tertiary dyke swarms are an established feature of the tectonics of North East Ireland, high-resolution aeromagnetic data provides excellent definition of considerable numbers of associated WNW-NW trending dykes, the ages of which are constrained by cross-cutting relationships with stratigraphic units, intrusions or faults. Four distinct swarms have now been distinguished, each of which shows different amounts of lateral displacement across NE-SW trending sinistral strike-slip faults, attesting to the broadly overlapping periods of dyke-related extension and faulting. Strike-slip faulting conforms to conjugate pairs of NE-trending sinistral and NNW-trending dextral faults, with displacements of up to 2.5km. Sinistral faults reactivate pre-existing Caledonian and Carboniferous structures, whilst dextral faults show no evidence of previous structure. NNW-trending dextral faults mapped from seismic data further to the south in the Irish Sea are believed to be the lateral equivalent of onshore structures which extend into the Lough Neagh Basin. The latter is characterised by thick sequences of both Oligocene clays and earlier Palaeocene basalts, and appears to represent a pull-apart basin close to the intersection of major dextral and sinistral strike-slip faults.

The activity of contemporaneous conjugate sinistral and dextral strike-slip faults with km-scale displacements which are attributed to approximately N-S Alpine compression may at first appear to conflict with the main orientations of dyke swarms. The pulsed nature of these swarms provides, however, a rationale for their formation in a tectonic regime characterised by Alpine-related deformation, with pulsed plume-related dynamic stresses and related deformation temporarily overwhelming the background far-field tectonic stresses and strain.

Magmatically Driven Fault Growth, Afar, Ethiopia

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Many studies on fault scaling relationships and fault growth have been undertaken in amagmatic regions, and/or in settings where faults are relatively mature. The active Manda-Hararo Rift, Afar, offers a unique chance to study the early stage of faulting in a magmatic rift. In 2005 the latest episode of rifting commenced with horizontal opening of up to 8m with vertical fault slip of up to 3m. Since then a further 14 dyke intrusions have been identified using InSAR and seismicity.

In order to quantify the fault slip and estimate fault growth patterns an airborne LiDAR survey covering 600 km^2 was conducted in October 2009. This provided app. 2 billion height measurements which we have gridded using the natural neighbour algorithm to produce a high-resolution Digital Elevation Model with 0.5m horizontal resolution. This large data set has let us to develop a method to automatically extract fault parameters for statistical analysis including displacement-length patterns. Fault traces, which have been picked manually by experts, are used to initially locate the fault and estimate strike. Perpendicular to strike equidistant cross-profiles are created and hanging- and footwall cutoffs are extracted using the horizontal gradient. Here we are presenting first results of this analysis using a subset of 500 faults. Preliminary findings show a significant number of individually mapped short faults with unexpected large vertical offsets suggesting them to be part of larger structures which might be linked at depth.

Structural Geological Processes Controlling Distribution of Permeability in UK Coals

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A good coal seam reservoir will hold 2 to 3 times more methane than same volume sandstone at like depth having 25% porosity and 30% water saturation. The key to accessing resource is to lower the reservoir pressure by dewatering the coal, thereby inducing desorption of the methane. And that requires good permeability. This talk outlines a project that sought to better understand the main processes controlling permeability variation in UK coals and, more generally, discusses the central role of structural geology in evaluation of so called unconventional gas resources worldwide.

Many inter-related processes can influence coal permeability but this project identified two of particular relevance to the UK: i) complex burial history in which UK coals have been buried up to 6km deeper before unroofing episodes in the Variscan, Early Cretaceous and Palaeogene, and ii) relation between fracture orientation and in situ stress, specifically whether it is possible to highlight areas where fractures are most conductive owing to their favourable orientation in the present day stress field.

CO_2 Dissolution From Inclined Fractures in Deep Saline Formations

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Supercritical CO_2 injected into a deep saline formation will eventually dissolve in the formation waters. The density of formation waters increases with CO_2 concentration and becomes negatively buoyant. In time convective instabilities could form and move CO_2 downwards away from the caprock. This is favourable for carbon capture and storage as it reduces the risk of CO_2 escaping through the caprock. The presence of a leaky fracture in the caprock could significantly jeopardise the security of a CO_2 storage complex. However, lateral diffusion and subsequent convection of CO_2 out of the fracture could increase overall dissolution rates. This paper presents a set of numerical simulations, using the TOUGH2-MP/ECO2N reservoir simulator, that explore the potential for convection enhanced CO_2 dissolution from leaking fractures. Simulations have been performed for varying fracture inclinations and Rayleigh numbers. We find that dissolution per unit area of fracture is increased for vertical fractures although total dissolution is increased for a larger fracture surface area. Also, higher Rayleigh number systems have higher mass transfer rates.

Patterns in the Locations and Characteristics of Natural CO_2 Seeps in Italy

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Italy is a region of anomalously high natural CO_2 degassing; it is estimated that over 5.3 Mt/yr of CO_2 is released through the crust from ~ 300 known terrestrial CO_2 seeps. These seeps exhibit a range of characteristics, with a variety of surface expressions, flux, compositions, and temperatures and can relate to travertine (continental carbonate) formation. Carbon isotope studies on these gases reflect a mixed origin; with varying proportions of mantle, crustal and biogenic sources.

There are clear broad-scale controls on seep distribution which reflect both deep processes and regional tectonics. Seeps concentrate in the western sector of Central and Southern Italy where the lithosphere is significantly thinned in comparison to the Eastern sector. CO_2 flux is much reduced in the Apennines, Italy's seismic belt, where unusual aftershock sequences have been attributed to the presence of trapped CO_2 fluids at depth. Within internal Central and Southern Italy, hydrocarbon exploration drilling frequently encountered CO_2 accumulations in reservoirs formed from flysch-topped thrust nappes. Some reservoirs are geographically related to CO_2 seeps which might imply breaching of the reservoir seal, or "leaky" reservoirs, analogous to leakage scenarios from engineered CO2 storage sites.

On a local scale, it is well known that faults control crustal fluid flow and the hydrogeological system. Indeed, springs in faulted environments are typically located at fault tips, regions of fault link-up (linkage, bifurcation etc) or along fault surface traces. It is expected that both wet and dry CO_2 seeps and travertine follow this fault association. The nature of the seep-hosting lithology is also expected to influence CO_2 seep expression and characteristics.

CO_2 gas seep, exploration and tectonic data allow us to identify and quantify the key patterns in the distribution and characteristics of CO_2 seeps using geostatistical methods. With this we elicit the controls on count density and flux of CO_2 fluids and their surface manifestations on both local and regional scales. The results are very interesting, and reflect the nature of CO_2 fluid flow pathways in a range of geological circumstance.

This research forms part of a PhD project which aims to better understand the plumbing of CO_2 fluids in the Earth's crust and model the architecture of CO_2 migration from complex seal reservoirs thereby guiding legislation for geological CO_2 disposal.

Porosity and Permeability Evolution of Faults in a Sandstones Analogous Reservoir in the "Bassin du Sud-Est", Provence, France

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Understanding the evolution of fault geometrical and hydromechanical properties during fault growth and network development is of major importance in fluid flow prediction in the crust. This question is particularly important for high porosity sandstone reservoirs, where brittle deformation generated low permeability cataclastic structures. Predicting the effect of these structures on bulk flow is crucial in the context of hydrocarbon production from faulted reservoirs.

This contribution is based on laboratory data of cataclastic deformation bands (CDBs) and larger ultracataclastic faults, from the Upper Cretaceous high-porosity sands and sandstones in the "*Bassin du Sud-Est*", France. Different methodological approaches are used in order to estimate the impact of the different geological factors which control distribution and localisation of deformation in sandstones. This study is based on three main research axes: (*i*) A systematic sampling on a large range of structures, kinematics and lithologies; (*ii*) A microstructural and a statistic porosity and granulometry analysis on SEM photomicrographs completed by laser granulometry measurements on the same samples; (*iii*) A permeability study based on the same large range of samples. Based on our different methods of analysis, the main results can be summarized as follows: (*1*) The SEM photomicrographs show: (i) A grain size reduction by grain crushing within the deformation bands; (ii) The grain-size and the porosity reduction evolve with increasing displacement and thickness. (*2*) The grain and pores size reduction is quantified by image analysis, and shows a two order of magnitude reduction between the host rock and a mature fault. The grain size reduction is confirmed by laser granulometry measurements. (*3*) There is a permeability reduction of 1 – 2 orders of magnitude from the host sands to the thin CDBs, but this becomes around 4 orders of magnitude perpendicular to the larger ultracataclastic faults.

These different analytical methods demonstrate the evidence of a transition in growth mechanism from thin CDBs to larger ultracataclastic fault zones. These larger fault zones form preferentially in contexts where a previous generation of CDBs already exists, suggesting the influence of previous structural heritage on further fault network growth and bulk reservoir permeability reduction.

Hydraulic Implications of Shallow Faults Dominated by Particulate Flow

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Fault arrays occur in shallow sediments as a response to both tectonic and gravitational processes. Heterogeneities developed as a result of sediment deformation along faults influence sub surface hydrological properties, with consequences for the management of water and energy resources. Despite the high frequency of faults within unconsolidated aquifers and reservoir rocks, the mechanisms of deformation, and their tangible implications for fluid flow, remain relatively unexplored.

We have studied a series of extensional faults (throws 0.1 to 100 m) cutting poorly consolidated sediment, in the Gulf of Corinth Rift, Greece. Within these faults strain is typically accommodated by distributed particulate flow – the sliding of individual grains along their boundaries, resulting in grain re-arrangement within the fault core. Significant rotation of individual grains, particularly larger clasts, occurs during particulate flow. Distributed cataclasis and grain comminution facilitate continued grain re-organisation within the fault, despite very low confining pressures. Cataclasis is most prevalent in regions of concentrated strain; proximal to slip planes, and within the centre of the fault core. Whilst distributed, grain scale deformation is not uniform across the fault core, probably due to micro-scale stress variations. Large-scale strain localization occurs in fine sediments as a result of clay smearing, or within sediments with greater mechanical strength caused by cementation. In faults where strain localization has occurred, lenses of sediment can be included within fault cores.

In spite of an initial dilatency of faulted sediments, offsetting and rotation of beds will increase the tortuosity of fluid flow paths. Pervasive particulate flow intensifies grain scale mixing and cataclasis, thus decreasing sediment sorting and permeability with fault evolution. The rotation of non-spherical grains with shear strain leads to along-fault permeability exceeding cross-fault permeability, and thus fault zone anisotropy. Lenses introduce blocks of fine, low porosity sediment into the fault core, potentially blocking fluid flow across and through the fault. Consequently, faults in poorly consolidated sediment will have an appreciable effect on fluid flow.

The Kinematic Significance of Imbricate Faults within Thrust Sheets

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The reasons for the development of imbricate shears at an angle to the principal thrust surfaces in zones of predominate simple shear has never been satisfactorily explained (at least to the author of this talk!). Somewhat surprisingly it is found that the positions of surfaces of maximum shear strain in deformation by simple shear are not parallel to the dominant surface developing the simple shear geometry, but are inclined to this surface at variable angles depending upon the amount of simple shear strain (usually specified by the quantity γ). These surfaces of maximum shear strain are correct in both orientation and shear sense to those which initiate and develop into the inclined imbricate thrusts. In any simple shear deformation there are two surfaces of maximum and minimum shear strain symmetrically disposed about the direction of maximum extension (longest axis of the finite strain ellipse). The positions of planes of maximum finite shear strain could account for imbricate thrusts, while those of minimum finite shear strain (with the same numerical shear value of the maximum shears but with opposite shear sense) are located at generally high angles to the predominate surface of simple shear and would give rise to local extensional shear surfaces such as are seen to predominate in overall extensional simple shear zones (eg. Basin and Range, USA).

There is strong evidence that, in parts of the Moine thrust imbricate zones, the overall basic simple shear displacement is accompanied by layer parallel shortening along the predominant simple shear surface (ie. parallel to the bedding in Cambrian sediments). The effects of this additional strain component have been analysed and it can be shown that the positions of maximum shear strain become more steeply oriented to the major thrust planes than is the case with simple shear alone.

The Tectonic Evolution of the Lucanian Apennines of Italy: Structural Constraints from the High Agri Valley

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The deformation history of orogenic belts is usually inferred from numerous observations carried out at different localities sparse over wide areas, whereas the complete sequence of structural stages is very rarely preserved within segments of limited extent. In this contribution we present the results of a study carried out along the central sector of the Lucanian Apennines, whose superb outcrop conditions make it possible to elucidate the deformation history of the southern segment of peninsular Italy.

The Lucanian Apennines are an arcuate fold-and-thrust belt developed due to imbrication of different tectonic units originated since Triassic time in distinct palaeogeographic domains. From Eocene time onwards the paleogeographic domains experienced contraction related to the subduction of the Tethys Ocean, and to the collision of the European and African margins. Stacking of the tectonic pile continued throughout the Early Miocene-Pleistocene time interval and progressively migrated towards the Apulian foreland. From Late Miocene time onwards thrusting was followed by the onset of normal faults that overprinted contractional structures. These normal faults truncate and offset two older generations of tectonic contacts that dip at moderate to low angles producing mainly extensional displacements. At odds with older thrusts and with more recent normal faults, the kinematics of low-angle tectonic contacts is not always well-constrained, and thus their tectonic significance remains problematic.

The results of our investigation provide new constraints that may enhance our understsanding of the kinematic evolution of the southern Apennines of peninsular Italy**.**

An extensional piggyback model for large apparent displacements along major "thrusts": Examples from the Norwegian Caledonides

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Collisional orogens are characterized by large-scale thrusts or nappes with postulated horizontal displacements exceeding 100 km. Examples are the Jotun and Trondheim Nappes of the Norwegian Caledonides, which are credited with ca. 300 km of lateral displacement. A model is proposed where initial thrusting is succeeded by passive transport on top of an exhuming high pressure/ultrahigh pressure (HP/UHP) metamorphic terrane. The initial thrusting is accomplished when two cratons (continents, microcontinents, arcs, etc.) collide and one is subducted beneath the other deeply into the mantle where it undergoes HP/UHP metamorphism. The subsequent exhumation of the subducted terrane occurs either by true extension, which effectively "pulls" the terrane out of the mantle, or by buoyancy driven extrusion, which allows the terrane to insert itself into the overlying crust bounded below and above by thrust faults and low angle normal faults, respectively, or by a combination of both mechanisms. The shear traction along the top of the exhuming terrane will reverse from earlier thrust motion (top to the foreland) to normal displacement (top to the hinterland). Shearing can detach the leading edge of the upper plate from the rest of the plate, allowing it to be carried passively towards the foreland on the exhuming plate with the displacement a function of the amount of exhumation of the lower plate. The Jotun Nappe and the Trondheim nappes were thrust (*sensu stricto*) towards the southeast and east, respectively, (present coordinates) during the early phases of the Scandian Orogeny when the western edge of Baltica was subducted into the mantle beneath the eastern margin of Laurentia where it was metamorphosed into a HP/UHP terrane, known as the Western Gneiss Complex (WGC). However, kinematic indicators along the basal decollement of the Jotun Nappe and perhaps the Trondheim nappes indicate a change in shear sense from top-east or southeast to top-west or northwest at essentially the same time WGC began its exhumation at ca 415 Ma. Normal sense shear along the top of the exhuming plate detached fragments of the leading edge of the overlying plate away from the main body, which were then carried passively east or southeastward as the WGC was exhumed. The total apparent displacement of ca. 300 km for the Jotun Nappe was only partly the result of thrusting; most of it was the result of piggyback transport on top of the exhuming HP/UHP terrane. Similar mechanisms can explain the present position of the Trondheim nappes and displacements of other nappes in this orogen.

Topology, Kinematics and Strain Variation within Strike-Slip Fault Networks

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Although the characteristics of individual faults and populations of such faults are well understood, their arrangement (topology) and resulting distribution of deformation within networks are less clear. Strike-slip fault networks at Westward Ho! (north Devon coast) and offshore Hartland Point have been investigated with the objective of determining their geometry, kinematics, and network topology.

The strike-slip faults in both areas comprise NE-trending left-lateral faults and NW-trending right-lateral faults that cut steeply dipping (~60°) and folded strata consisting of sandstones, siltstones and mudstones. The faults were accurately mapped in the field and from aerial photography (at Westward Ho!) and multibeam bathymetry data (at Hartland Point), and lateral separations of marker beds were measured along the fault traces. These data were used to calculate variations in the density and relative proportions of the fault sets as well as a tensor analysis of the strain. A scaling analysis involved extracting fault segment data at different resolution cut offs and was used to investigating the distribution of strain, fault density and connectivity within the network.

The results from Westward Ho! show a range of heterogeneity within strike-slip fault networks, both in terms of the fault patterns and strain. Some sub-areas show a dominance of one fault set, with regularly spaced larger displacements, separating relatively weakly deformed blocks with smaller antithetic faults. Within these areas up to 20° rotation of the faults and bedding produces a domino style deformation that accommodates up to ~15% extension. The domino regions are separated by areas of conjugate faulting, in which both sets of faults are equally developed and have similar displacement ranges. Conjugate areas have little or no rotation of the bedding and generally have lower strains than the domino regions.

The scaling analysis show that the majority of the strain is localized on the larger faults within a network, with over 80% of the overall extension being taken up by faults with >10m displacement. The connectivity of the network was analyzed in terms of the proportion of nodes that connect branches, which increases with increasing resolution. Hence strain is controlled by the larger fault segments whereas the connectivity is reliant on the presence of smaller faults.

U-Pb Dating of Brittle Deformation

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Fault planes and fractures are amongst the most commonly observed expressions of brittle deformation in the uppermost crust. The absolute ages of these structures are difficult to determine, since only few minerals grow at such low temperatures. Depending on lithology and fluid flow, syndeformationally grown mineral fibres ("slickenfibres" on fault planes or "tension gashes" in case of filled fractures) occur. This study evaluates the possibility of dating these minerals with radiogenic isotopes. This would add valuable temporal information to the deformation kinematics that are recorded by the growth direction of the fibres.

Specifically, we attempt to date calcite slickenfibres and tension gashes – collectively referred to as "tectonic carbonates" – using the U-Pb method. Under favourable conditions, calcite incorporates uranium preferably over Pb, resulting in high U/Pb ratios, and preserves the isotopic system well enough to allow a precise age calculation. This has been successfully applied to calcite from sedimentary, chemogenic and biogenic environments. We developed and optimised the U/Pb analytical workflow for the U and Pb concentrations typically observed in tectonic carbonates.

We utilise laser ablation inductively-coupled plasma mass spectrometry (LA-ICPMS) for pre-screening of samples for their U and Pb concentrations and spatial distribution. The latter allows to choose the best portions of a sample for further microsampling. U and Pb are separated from the microsamples with ion exchange chemistry followed by analysis of the isotopic composition on a multi-collector ICP-MS.

Here, we present an overview over the difficulties and uncertainties in U-Pb dating of tectonic carbonates and our approaches to overcome them, together with results of some case studies from select areas in the Alps. The sampling areas were chosen where ages of deformation are well established in the literature, to better evaluate the reliability of the new method.

Shortfalls in Contraction from Submarine Thrust Belts Imply Substantial Lateral Compaction – Insights from the Namibia Continental Margin.

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Paired extensional-contractional tectonics, driven by the large-scale gravitation collapse of the sedimentary wedges on passive margins, offer ideal sites for evaluating how deformation is partitioned into folding, faulting and other mechanisms. In this study a regional seismic line, 215 km long, is used that traverses the African continental margin offshore Namibia. Along this margin the post-rift megasequence displays extensive down-to-the-ocean gravity slide systems. The seismic profile here shows such a system, bounded oceanward and landward by apparently undisturbed sedimentary successions. Deformed successions occupy a margin width of about 180 km. Down-dip contractional structures link via a detachment to an extensive array of extensional faults and their syn-kinematic sediments. Total extension is best determined using the total fault heave along the detachment. This is 71 km, a figure that reduces to 44 km if residual pre-kinematic strata are included. Stratal reflectors in the well-imaged thrust belt restore to a maximum pre-kinematic width of 85 km and a maximum net contraction of 25 km. The disparity between extension (>44 km) and contraction (<25 km) can only be resolved by appealing to seismically unresolved distributed strain. Comparisons with stratal thicknesses oceanward of the deformation do not resolve measurable distributed vertical stretching in the thrust belt. The only solution that satisfies the kinematic requirements of the seismic interpretation is widely distributed volume loss, through lateral compaction and concomitant reduction in porosity. If distributed through the contractional domain this equates to 18% - 25% volume loss. This value can be reduced, perhaps by a factor of 2, if also distributed into the down-slope parts of the extensional domain and out ahead of the thrust belt. This deformation pre-dates localization of thrust faults and is not depth-dependent at the resolution of the study. There are significant issues for the structural evolution of thrust belts in non-fully lithified sediments – whether of tectonic origin or gravity-driven.

Seismic data and the interpretations presented here are available on the Virtual Seismic Atlas (www.seismicatlas.org). Data are courtesy of CGG Veritas. Some of this contribution is available in GSA Today (March 2010).

The Utility of Theoretical Forward Modeling Algorithms to aid Cross Section Construction in a Foreland Fold-thrust Belt

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While kinematic restoration has regularly been applied to validate cross-sections, forward modeling has typically been left as a final check on the geometric compatibility, or as a test of the stress and/or strain regime in a section. This work instead utilizes forward modeling at an early stage to aid the section construction process in Bornes-Aravis massif of the French Subalpine chains – a classic foreland fold-thrust belt. Surface readings, from geological maps and fieldwork, comprise the majority of data in the area. As a result, information on the deep geological structure is limited, with the fault architecture particularly uncertain, leading to difficulties when attempting to draw cross-sections. Kinematic forward modeling algorithms have been applied to test a number of possible fault configurations and deformation styles. The advantage of carrying out forward modeling to aid the section construction process is that a number of scenarios can be quickly tested to help arrive at a plausible solution in a short period of time. Of wider significance is the assessment how applicable theoretical kinematic models of fault and fold development are to the subalpine chains and other fold-thrust belts.

Ellesmerian tectonism in the Canadian Arctic Islands: the end of the Franklinian Passive Margin

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The Canadian Arctic Islands are situated on the northern margin of the North American continent. The region is reported to have undergone a complete Wilson cycle from the Neoproterozoic to the Devonian. In the Neoproterozoic, rifting occurred along the northern margin Laurentia, and the Franklinian passive margin formed. Sedimentation along this margin was continuous from the Cambrian to the early Devonian. Middle to late Devonian clastic strata, interpreted as a southwest prograding clastic wedge, are preserved across much of the Canadian Arctic Islands. The onset of clastic wedge sedimentation represents a switch from a passive margin depositional setting to a foreland basin depositional setting which formed following the Silurian accretion of Pearya, an exotic terrane, to the passive margin in northern Ellesmere Island. Sedimentation along the entire Franklinian margin ceased altogether when much of the Franklinian succession was deformed and uplifted during the late Devonian to early Carboniferous Ellesmerian Orogeny. However, the extent and timing of Ellesmerian tectonism in the wider circum-Arctic region are uncertain. Furthermore, evidence for many of the processes usually involved in orogenesis, such as metamorphism, a collisional core zone and post-tectonic magmatism are absent in the Canadian Arctic. So what was the geodynamic cause of the Late Devonian to early Carboniferous tectonism?

CASP fieldwork in 2009 and 2010 targeted two areas on Ellesmere Island: the Lake Hazen area in the northeast and the Raanes Peninsula area in the southwest. These two areas, approximately 500 km apart, contain very different sections through the Franklinian succession. At Lake Hazen, polydeformed Cambrian rocks are in fault contact with Permian to Cretaceous strata of the Sverdrup Basin. On the Raanes Peninsula, folded Ordovician to Devonian strata are unconformably overlain by, and in fault contact with, Carboniferous to Cretaceous strata of the Sverdrup Basin.

A comparison of the structural geology of the field areas visited by CASP provides constraints on the extent and timing of the Ellesmerian deformation documented on Ellesmere Island. Comparison with other areas in the circum-Arctic is the key to generating a model that explains the geodynamic cause of this enigmatic orogeny.

An Introduction to Intermediate Crust (IC): its Formation, Epeirogenic Character, and Plate Tectonics Significance

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The plate tectonics paradigm currently posits that the Earth has only two kinds of crust - continental and oceanic - and the former may be stretched or the latter modified by arc/collision until it looks continental. But in seeking the 'continent-ocean boundary' (COB) along passive margins we need to think how the MOR process there would have been affected by heavy concurrent sedimentation. The evidence is that this, by blocking the hydrothermal cooling, inhibits magnetic anomaly formation and prolongs magmagenesis to give a much thicker mafic crust, here called IC, to distinguish it from Mature Continental Crust (MCC). I have shown (2008, *Int.Geol.Rev*. **50**, 685-754) that the hydrous content of deep MCC and of deeply subducted UHP slices gives them a big thermal epeirogenic sensitivity which IC lacks. My global analyses of block-and-basin (B&B) layouts within continents, begun in 1966, have shown, remarkably, that their MCC, identified by uplift and often by exposed geology, can be reconstructed by reversing a sequence of very precise (locally <5km) IC-generating separations, commonly in differing directions, such that the second was only made kinematically viable by the first. Clearly not a matter of chance!

The final step in this interpretation, and in justifying it here, is to explain the remarkable tightness dictated by the geometries, and the spreading of thermal rejuvenation to far from the present COBs. My analysis of global plate dynamical behaviour since ~150Ma (*Geophys. Res. Abstr.* **11**, EGU2009-6359; **12**, EGU2010-6101) shows that, for a petrological reason, LVZ material is actually very stiff and tectospheres reach >600km below cratons and even to >100km at MORs. To meet the latter requirement I offer my 25yr-old model for constructing thick plate at MORs. It has a deep, laterally-accreting, narrow (20cm?) mantle crack. So even a curved splitting line is precisely followed, as the B&B geometries require. I show 3 example analyses, each a record of relative plate motions:- (1) Shelf-forming 2-stage separation of Greenland-Svalbard from Norway after Scandian thrusting of the Greenland-built Western Gneiss onto Norway; (2) 5-stage Siluro-Devonian sequence in central Ireland; (3) Calabria, documenting 3-stage Permian(?) CCW rotation of Adria.

Shifts in the Intertropical Convergence Zone and the Tectonics and Climate of the India-Eurasia Collision

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The Early Miocene (~23 – 16 Ma) was the time of peak Himalayan exhumation and postulated mid-crustal channel flow in the High Himalayas – a tectonic configuration not recognized before or after in the range. Previous models have correlated this rapid exhumation with the onset of the Asian monsoon, and/or suggested that it contributed ultimately to mid-Miocene global cooling, via silicate weathering and/or organic carbon burial, and consequent atmospheric CO_2 drawdown. Based on published Pacific Ocean sedimentation records and India-Eurasia plate reconstructions, we compare the position of the Intertropical Convergence Zone (ITCZ) with the palaeolatitude of the Himalayas, and show these converged in the Early Miocene. As the ITCZ is a zone of high precipitation, we suggest that this convergence was an important driver of Early Miocene High Himalayan exhumation and erosion. Continued northwards motion of the Indian plate took the Himalayas north of the ITCZ, which migrated south through the remainder of the Miocene. High Himalayan exhumation and ductile shearing correspondingly decreased after the Early Miocene. This mechanism for increased Himalayan erosion is independent of the timing of the onset or enhancement of the Asian monsoon, which is debated.

A variety of climate proxies from across Central, South and East Asia have yielded different ages for the start or intensification of a monsoon climate system. Common estimates include the early part of the Early Miocene (~23-20 Ma) and the Late Miocene (~11-8 Ma). We propose that increased seasonality in the Late Miocene in the Himalayas and neighbouring regions was a response to an increase in the distance between the ITCZ and the Himalayas/Tibet, such that the ITCZ was only brought northwards during the northern hemisphere summer each year. This is essentially the pattern of the modern South Asian monsoon system. These climatic changes coincide with a switch from north-south extensional shear on the northern side of the High Himalayas and thrusting on the Main Central Thrust, to thrusts further south in the Himalayas (Main Boundary Thrust). We speculate that the tectonic changes were at least in part a response to a reduction in precipitation over the High Himalayas: the Himalayan thrust belt re-organised to maintain a critical taper appropriate to a drier orogen.

Ref: H.A. Armstrong & M.B. Allen, Shifts in the Intertropical Convergence Zone, Himalayan exhumation and late Cenozoic climate, ***Geology****, in press.*

Estimating the viscosity of the Tso Morari Gneiss Dome, Western Indian Himalaya

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The Tso Morari Gneiss dome in the Indian Himalaya extruded from a depth of ~200 km through an inclined channel of elliptical cross-section at the leading edge of the Indian plate by means of Poiseuille flow with a Newtonian rheology. The velocity profile of this gneiss dome is derived after (*i)* finding the "best fit" of the outcrop of the gneiss dome to an ellipse; *(ii)* taking the three different lithologies at the top of the extruding gneiss to have acted as a single plug; and *(iii)* taking the extrusion to have been driven by the buoyant push of the denser mantle beneath the lighter gneiss. Fitting the known rates of extrusion of this gneiss dome to its velocity profile constrains its maximum viscosity to be ~ 8×10^{23} Poise. The maximum value is higher than the previous estimates for gneisses elsewhere (e.g. 2.8×10^{21} Poise, 8×10^{19} to $<1.66\times10^{22}$ Poise, and 10^{20} Poise). We use geological arguments to justify neglecting in our calculations the geothermal gradient, erosion, gravitational spreading and the compositional heterogeneity of the dome. Our approach to constraining the viscosity of an extruding rock mass could be applied to many other terrains.

Formation of the West Siberian Basin by the Decay of a Plume Head

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The West Siberian Basin (WSB) is one of the largest intracontinental basins in the world with and area of roughly 3.5 million km^2. It is closely associated with the Siberian flood basalts which underlay the sediments and extend on to the neighboring Siberian Craton. However, the mechanism which formed the basin is still uncertain. Rifts have been observed on seismic and magnetic surveys in the north of the basin, but the basin size far exceeds the extent of the rifts. The sediment thickness varies between the rifted areas and the wider basin. In the rifts well logs show ~ 8 km of sediments. In areas of the basin out with the rifts the average sedimentary thickness is ~ 4 km thick. The reverse is seen in the crustal thickness, where the moho beneath the rifts is at a depth of ~34 km and is deeper (~38 km) in the wider basin. The sedimentation in the rifts begins almost immediately after the eruption of the basalts 250 Ma and continues through to the present day. Outside the rifts the top of the basalt, where it is present, forms an erosional surface and sediment deposition doesn't begin for 50-70 Myrs with the first basin wide transgression seen at 164 Ma. We used a numerical 1D conductive heatflow model to calculate the isostacy and temperature change through a 170 km thick column of the crust, lithosphere and upper mantle. This was used to test whether the cooling of a hot layer at the base of the lithosphere could explain the basin formation. We found that cooling of a 1500 ˚C 50 km thick layer below a 50 km thick lithosphere fitted the subsidence curves from the within the rifts if a 34 km thick crust is used. It also fits those from the wider basin when the crustal thickness is increased to 38 km even showing the delayed onset of subsidence seen. The thickness and temperature of the hot layer and extent of thinning of the lithosphere match observations from present day plumes and numerical models of plumes. Therefore we propose that the WSB formed due the decay of a plume head at the base of the lithosphere which caused uplift and rifting of the crust and thinning of the lithosphere accompanied by eruption of the Siberian flood basalts. This is followed by subsidence as the plume head cools. The initial uplift outside the rift has to drop below sea-level before sedimentation is seen outside the rifts explaining the delay.

Regional Magnetic Fabric Study of the Plougastel Formation in the Western Central Armorican Terrane (Brittany, France)

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The western part of the Central Armorican Terrane (WCAT), a low-grade middle- to upper-crustal domain exposed in the Armorican Massif (Brittany, France), is affected by an early Variscan contraction-dominated deformation event. Our work consists of a regional magnetic fabric analysis of homogeneous siltstone beds (HSB) in the Plougastel Formation (Pridolian to Lochkovian) that are exposed in different structural settings and levels of the WCAT. Macroscopically, the HSB's show no internal bedding fabric. However, the anisotropy of magnetic susceptibility (AMS) systematically reveals a composite magnetic fabric, composed of both a bedding-parallel and a cleavage-parallel magnetic-carrier population. Based on petrography, demagnetization experiments and XRD analyses, we show that the bedding-parallel magnetic signal arises from a subtle rock fabric composed of ferromagnetic minerals with a strong internal anisotropy or Fe-rich phyllosilicates. The cleavage-parallel magnetic-carrier population is composed of micas. Despite a positive correlation between the degree of anisotropy (P_J) and the intensity of the mica XRD peak, the AMS signal arises from a complex interaction between both carrier populations. Thus, low-field AMS of a composite magnetic fabric cannot be used as a strain marker, without a more integrated approach (e.g. anisotropy of anhysteretic remanence magnetization (AARM) and low-temperature AMS).

A Dip Isogon Method for Distinguishing Folded Structures in Sediment and Rock

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Apparently identical fold structures are observed to develop in both unlithified (sediment) and lithified (rock) materials. It may prove difficult therefore to distinguish between their different modes of origin, particularly as the former eventually become lithified. To test whether geometric differences exist between these two types of fold structures, the dip isogon and quantitative bed thickness methods (Ramsay, 1967) have been applied to slump beds (i.e. folded sediment) from Powys, Central Wales and meta-sediments (i.e. folded rock) from Roscolyn, NW Wales. Using these methods, diagnostic criteria have been established that distinguish folding in unlithified and lithified materials. Folded sediments are characterised by: (1) asymmetric dip isogon patterns and bed thickness ratios about fold hinge zones; (2) scattered, repeating dip isogon patterns and bed thickness ratios on fold limbs; and (3) lack of conformity to any specific 'Ramsay' dip isogon fold class across the folded layer. Folded rocks behave in an essentially opposite manner and are characterised by: (1) symmetric dip isogon patterns and bed thickness ratios about fold hinge zones; (2) ordered, non-repeating dip isogon patterns and bed thickness ratio on fold limbs; and (3) conformity to a specific 'Ramsay' dip isogon fold class across the folded layer. These criteria have been applied to the Upper Carboniferous Bude Formation fold-thrust belt, SW England, where the supposedly Variscan tectonically-generated 'upright' chevron folds exhibit the diagnostics expected for folded sediments and the 'inclined-to-recumbent' chevron folds exhibit the diagnostics expected for folded rocks. The model described here to distinguish between folded sediments and rocks may have important implications for understanding the evolution of fold-thrust belts developed in delta toes and foreland basins.

Eye and Sheath Folds in Turbidite Convolute Lamination: Aberystwyth Grits Group, Wales

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Eye and sheath folds are described from the turbidite sandstones of the Aberystwyth Group, in the Silurian of west Wales. They have been studied at outcrop and on high resolution scans of cut surfaces. The folds are syn-sedimentary rather than tectonic in origin. They occur as part of the convolute-laminated interval of sandstone-mudstone turbidite beds. The thickness of this interval is between 40 and 210 mm and is most commonly between 70 and 130 mm. Lamination patterns confirm previous interpretations that convolute lamination nucleated on ripples and grew during continued sedimentation of the bed. The folds amplified vertically due to buoyancy forces and were sheared horizontally by continuing current flow, but only to average shear strain values of about 1. The strongly curvilinear fold hinges are due not to high shear strains but to nucleation on sinuous or linguoid ripples. Folds decay in amplitude towards the top of each turbidite bed and are overlain by parallel-laminated mudstone.

Plots of the size and shape of the convolute lamination eye folds place them firmly within the range of structures observed in metasedimentary rocks. The Aberystwyth Group structures therefore give a warning that eye folds in metasedimentary rocks should not necessarily be interpreted as sections through high-shear-strain sheath folds.

Graded sand-mudstone beds of the Aberystwyth Group. Only sandstones thicker than 40 mm are convolute laminated. 15cm pencil scale.

Eye fold in convolute-laminated sand turbidite bed. 5cm scale bar.

What is a Salt Structure?

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Here we explore the physical definition and seismic interpretation of salt structures. Three topics are considered – a framework for salt tectonics, aliasing of other mobile materials, and geophysical imaging issues.

A key to understanding salt deformation is the triggering and driving mechanisms of salt movement. Work in complex salt basins such as the Gulf of Mexico has demonstrated a diversity of structures including diapirs, walls, sills - and welds where there is no salt at all. It is also clear that the space problem arising when salt moves from its autochthonous position is accommodated by deformation of strata adjacent to the salt. This deformation defines a related suite of structures, intimately associated with salt movement. Triggers of salt movement are nearly always external to the salt itself, such as regional or gravity tectonics. Given that salt is usually a weak, mobile layer, a different perspective on salt tectonics is that salt generally forms accommodation structures and the primary structures are those in the adjacent strata. So salt tectonics could be thought of as variants of regular tectonic styles such as extensional tectonics, gravity tectonics and so on.

If ground-truthing data are rare or absent, it may not be clear whether a given structure is related to salt, mud or igneous material. This aliasing is due to common processes of redistribution and intrusion of mobile material. Geometric families of structure can be defined that relate mud, igneous and salt intrusions. Telling these apart on the basis of reflection seismic imaging alone is not always straightforward.

A further challenge concerns the lens through which salt structures are viewed. Much effort has gone into reflection seismic acquisition techniques, for instance depth migration can make a good job of securing an accurate image of the top, sides and base of allochthonous salt. Another issue in the interpretation process is that reflection seismic is rarely displayed at 1:1 aspect ratio, in fact 75% of seismic is displayed with a vertical exaggeration of 2 or more. So structures in salt and adjacent sediments are usually seen with a vertical stretch that affects dips, curvature and cutoff relationships.

What Drives Salt Flow in the Gulf of Mexico?

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Salt tectonics at passive margins is currently interpreted as a gravity driven process but according to two extremely different types of models: i) spreading only driven by differential sedimentary loading and ii) gliding primarily due to margin tilt (slope instability). Since three decades, it has been commonly assumed in the northern Gulf of Mexico that salt has flowed toward S or SE as a result of differential sedimentary loading since its deposition in Jurassic.

The kinematics of regional-scale salt flow can be directly constrained using: i) the migration of shelf break contours at the termination of successive depositional episodes, ii) the relative horizontal displacements of minibasins displayed at seafloor and iii) the location and geometry of large-scale structures of the slope domain as imaged by seismics. In the north margin, salt has flowed toward the SW since the Cretaceous, with three main stages of development prior to, during and after frontal failure and massive salt extrusion in the Early Miocene. The corresponding sequence of structural development is discussed using a laboratory model in which a sedimentary progradation was made with a 60° obliquity to margin dip. The model illustrates the dynamics of shelf migration and the drastic change in deformation pattern due to frontal failure.
Contrary to all previous interpretations that invoked sedimentary loading as the main driving force, the analysis of regional-scale salt flow implies that salt tectonics of the northern Gulf of Mexico is predominantly controlled by gliding above a SW-dipping margin. This indicates that the north margin of the northern Gulf of Mexico trends NW-SE, in agreement with plate kinematic models in which the Yucatan continental block has undergone a 45-60° sinistral rotation.

Using Polygonal Fault Systems to Reconstruct the State of Stress Associated With Salt Diapirs

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Using 3D seismic data from the eastern Central Graben, North Sea we show how the geometry of polygonal fault systems can be used to reconstruct the state of stress around salt diapirs. Polygonal faults are non-tectonic fault systems that develop during early burial and compactional dewatering. Under passive loading of a horizontal substrate undergoing 1-d consolidation, the maximum principle stress (σ_1) acts vertically downward. The intermediate and least principle stress, σ_2 and σ_3 - respectively, act in the horizontal plane without any preferred orientation, giving rise to a polygonal fault pattern. In seismic data polygonal fault systems are organised into a series of stratigraphically confined intervals (tiers) which are representative of distinct periods of deformation.

Seismic data shows that stratigraphic units containing polygonal faults have been pierced by several salt diapirs. Dip maps of horizons within polygonal fault tiers show that closely spaced radial fault sets exist close to the salt margin and merge into polygonal faults at varying distances from the salt diapir. The width of the radial fault zone approximates the diameter of the salt diapir but is seen to vary throughout different tiers. Critically, fault mapping and analysis shows that radial faults are tier bound indicating that radial faults are preferentially aligned polygonal faults, termed here hybrid polygonal faults.

Hybrid polygonal faults allow us to map the change in orientation of the intermediate stress (σ_2) which is parallel to fault strike. We attribute the radial alignment of polygonal faults to the circumferential stretching that occurs in sedimentary units onlapping a growing diapir. By calculating and mapping the palaeo-stress for successive polygonal fault tiers we present an alternative approach for reconstructing salt growth that provides novel constraints on relative magnitudes and orientations of the principal stresses. We use the calculated salt related stress field from different PF tiers understand the evolution and different growth phases of the ECG salt diapirs. In particular we look for evidence that supports or discredits a common late active diapir phase in response to alpine compression in the Middle Miocene.

Large-scale, Basement-controlled Segmentation of an Evaporite-Detached Fault System: Eastern Margin of the Halten Terrace, Offshore mid-Norway

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The Halten Terrace, offshore mid-Norway, is underlain by two evaporitic units of Triassic age, each approximately 380 m thick and separated by approximately 530 m of mudstone. This evaporitic package is rheologically weak, and led to decoupling of fault systems during Middle Jurassic to Early Cretaceous rifting. We examine 3D seismic data, constrained by wells, from the eastern margin of the Halten Terrace, including parts of the Bremstein and Vingleia fault complexes. Mapping of faults and key seismic horizons, and analysis of throw and strain variations along the fault systems, allow us to identify patterns of large-scale fault segmentation and constrain the relationship between sub-salt and supra-salt parts of the fault system.

The eastern margin of the Halten Terrace is made up of a 10 km wide array of supra-salt restricted normal faults. The supra-salt structures are linked to basement structures, either through thick-skinned faults that displace the evaporite package, or through soft linkage to sub-salt restricted faults. Based on structural style and dominant fault strike, three structural domains can be identified on the basis of dominant fault strike and structural style; northern and southern domains dominated by NE-SW striking thick-skinned faults are separated by a central domain dominated by N-S striking thin-skinned faults. The boundaries between these domains correspond approximately to i) the positions of fault tips or relays along major basement-involved faults, and ii) the positions of sharp changes in both summed throw and estimated strain across the fault system. The northern and southern domains accommodate higher strains than the central domain. We suggest that these observations are the result of a number of factors, including i) The presence of pre-existing basement faults that were reactivated during Middle Jurassic to Early Cretaceous rifting, ii) the orientation of fault systems with respect to stress orientations, and iii) variations in evaporite facies.

Three-dimensional Reconstruction of the Cotiella Extensional Listric Growth Fault System (Southern Pyrenees of Spain)

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The Cotiella Massif is located in the southern Pyrenees of Spain. The Pyrenees is a Late Cretaceous – Early Miocene thrust and fold belt developed from the inversion of previous Mesozoic extensional basins (Muñoz, 2002). The Cotiella s.s. thrust sheet consists of a 4 km succession of Upper Albian to Lower Santonian post-rift units (Souquet, 1967, Séguret, 1972; Garrido and Ríos, 1972). This post-rift succession unconformably overlies the pre-rift Triassic evaporites.

García-Senz (2002) and McClay et al. (2004) proposed that the internal structure of the Cotiella thrust sheet is constituted by seismic-scale, northwards-dipping, extensional listric growth faults, gliding over the Triassic shales during the Coniacian - Early Santonian post-rift stage. This late Cretaceous extensional fault system has been interpreted to be formed by gravity-driven extension over a salt detachment in a manner similar to that proposed for the South Atlantic passive margins (McClay et al., 2004). The extensional faults were reactivated during Pyrenean shortening as large hanging-wall antiforms, some with an overturned rollover core. Nevertheless in all cases the original extensional features of the listric growth faults can be recognized.

The internal geometry of the Cotiella fault system conjugates linked frontal ramps and transfer faults with rapid losses of fault displacement, that result in significant thickness variations, rapid facies changes and complex growth strata patterns, which could not be fully understood via cross-sections construction and are more suited for 3D modeling. In this communication we deal with the 3D reconstruction of this exceptionally well-preserved extensional listric growth fault system.

Using Hydrology to Constrain Flow Rates of an Active Salt Extrusion in Iran

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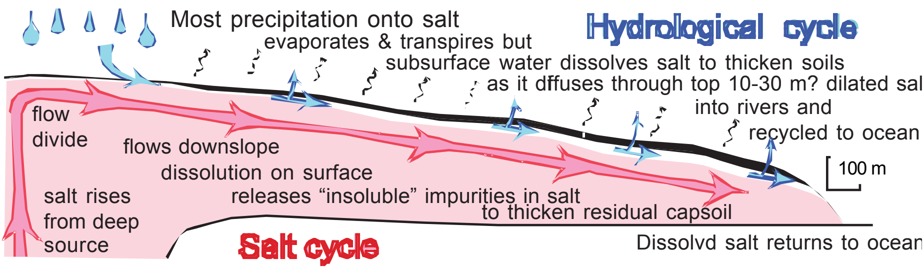
A novel route is taken to constrain the rates of flow in Konarsiah, an active salt extrusion in the Zagros Mountains of Iran. The salt cycle is outlined as exemplified by ~150 extrusions of salt in the Zagros and show that the Konarsiah extrusion has a shape close to that of a viscous droplet. Three years of measurements of displacements of marker near the summit are available but are very variable; here we use the hydrology to constrain longer-term rates.

Standard hydrological measurements (Zarei & Raeisi, 2010: Carbonates Evaporites: DOI 10.1007/s13146-010-0027-0) were used to estimate how much salt was dissolved from Konarsiah in 2007/8. The rainfall not lost by evaporation and transpiration dissolves some of the outermost 10-30 m (?) of salt to generate surficial residual soils. After correcting the low rainfall of 2007/8 to the 25-year mean, the likely rates at which such soils thicken are constrained. Soil thicknesses with distance from the summit are then used to constrain the age of the distal salt and then the rates of horizontal salt flow and vertical supply from depth.

The soils that mantle Konarsiah limit the range of classical karst features and probably also subdue flow surges after occasional rainstorms. Small closely-spaced solution dolines in new salt near the summits enlarge as they are carried downslope and joined by collapse dolines and a few shafts and inlet caves that all fall off the steep salt margins. Cave systems appear to be missing, if only because most of the salt deeper than ~10-30 m is impermeable because it is still flowing.



At what rates does salt pass through this system?

Tsaoling and Jiefengershan landslides: two catastrophic landslides triggered by 1999 Taiwan Chi-Chi earthquake as studied by high velocity friction experiments

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Recent development in rotary-shear low to high-velocity frictional testing machines has made it possible to study fault properties at very wide slip rates from plate motion on the order of several tens of mm/year to seismic fault motion reaching several m/s. Studies with those machines have elucidated intrafault processes and mechanical properties during seismic fault motion, demonstrating that nearly all faults dramatically weaken at high velocities. Catastrophic landslide is another phenomenon in that high-velocity weakening of slip surface seems to cause high-speed landslide motion. Landslides along flat bedding planes of sedimentary rocks, along flat surfaces such as joints or fractures, or along thin slip surfaces have similarities to fault motion. After brief review of testing machines, we will present our recent experimental results on two catastrophic landslides in Taiwan triggered by the 1999 Chi-Chi earthquake (Sept. 21, 1999, M_w 7.6).

Tsaoling landslide is the largest with landslide volume of about 130 Mm^3. and Jiefengershan landslide is the second largest with about 50 Mm^3.in volume among over 20,000 landslides triggered by 1999 Chi-Chi earthquake. Both occurred along flat bedding planes of sandstone and siltstone of Neogene sedimentary rocks. Bedding planes are nearly parallel to mountain slopes. Bedding-parallel faults are locally developed due probably to flexural slip folding of anticlines and synclines widely developed in the area. XRD analyses show that both siltstone and fault gouge contains kaolinite, illite, smectite and chlorite, with no marked differences in mineral composition between the two. A seismic record and a survivor's witness indicate that the average speed of Tsaoling landslide reached 20 to 40 m/s (80-140 km/hour) which requires that the friction reduces down to the level of 0.05 to 0.15. Our high-velocity experiments exhibit that friction at velocities over 1 m/s reduces exactly to that level. Slope of Tsaoling landslide is 14º, smaller than the friction angle, and we show a possible landslide-triggering process by seismic ground motion by sinusoidal acceleration/deceleration experiments. On the other hand, the slope of Jiefengershan landslide is 20-36 º, larger than the friction angle we measured. The landslide mass must have been supported by sandstone layer extending all the way down below a flat river terrace. Breaking of this layer by seismic ground motion is likely to have triggered the catastrophic Jiefengershan landslide.

The geochemical signature of carbonate-hosted seismogenic faults

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Laboratory experiments have been performed at sub- (≈ 0.01 m/s) to seismic slip rates (>1 m/s) on dolomite gouges of the Triassic Evaporites in Northern Apennines (Italy), which hosted the 1997 Colfiorito $M_w \leq 6$ earthquakes.

Experimental faults are lubricated as marked falls in the steady state sliding friction coefficients, $f \approx 0.1$, is observed at seismic slip rates, as opposed to values of $f \geq 0.6$ attained for sub-seismic slip rates. Fault lubrication was associated with decarbonation reactions and CO_2 emissions triggered by frictional heating in the experimental slip zone which produced: 1) new and exotic mineral phases (e.g. Mg-calcite, periclase/brucite, lime/portlandite); 2) isotopic fractionation between the newly generated and the original mineral phases.

When extrapolated to natural seismic fault conditions, experimental results show that coseismic release of CO_2 can represent a shallow and localised source of very high fluid fluxes in the brittle crust, comparable to measured fluxes from deeper sources (e.g. mantle degassing). Modelling results show that when large amounts of coseismically released CO_2 interact with deep saline aquifers, the geochemical signature produced may be very weak and difficult to detect in groundwater. Conversely, it should be possible to measure and monitor the geochemical signature of large amounts of coseismically released CO_2 which are directly dissolved in shallow, less saline aquifers.

We conclude that the integration of microstructural/mineralogical observations and geochemical data from experimental faults allow the definition of a distinct and measurable geochemical signature associated with high temperature physical-chemical processes. During earthquake propagation in natural carbonate fault zones, the operation of the same processes observed in the laboratory can: a) release significant amounts of CO_2, which are comparable to those released by deeper sources (e.g. mantle degassing); b) represent a relatively shallow and localised source of very high fluid fluxes of CO_2 in the brittle crust; c) produce groundwater post-seismic geochemical signatures which can potentially be measured and monitored, depending on the geochemical nature of the aquifers present at different depths.

Relationship between normal faulting and volcanic activity in the Taranaki backarc Basin, New Zealand.

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The spatio-temporal evolution of normal faulting and submarine volcanism during Mid-Miocene-recent times in the Taranaki backarc basin, New Zealand, highlights features related to subduction zone processes. High sedimentation rates have led to the blanketing and preservation of volcanic edifices and normal faults imaged on regional seismic datasets, providing a basis for defining the evolution of fault and volcanic activity. Southward migration of the locus of volcanism and basin extension is linked to steepening and migration of the Hikurangi subduction zone between the Australian and Pacific plates, but volcanic activity shows a more gradual southward progression, compared to the punctuated migration of fault activity and basin location. Stepwise changes in the locus of faulting is attributed to periods of strong coupling between the subducting slab and the overlying crust, with consequences for crustal deformation throughout New Zealand. The spatio-temporal migration of subduction-related faulting and volcanism can, therefore, differ, with neither process controlling the location of the other.

Soft-sediment Deformation Within Slumps Around the Dead Sea Basin

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The Late Pleistocene Lisan Formation preserved next to the Dead Sea provides exceptional 3-D exposures of folds and faults generated during soft-sediment slumping and deformation. Vergence of sedimentary slump folds outcropping to the West of the Dead Sea is systematically (>90%) towards the East (in agreement with many other criteria such as thrusts) and consistent with depocentre-directed slumping. This study recognises for the first time that on a regional scale, the direction of slumping inferred from the fold and thrust geometries noted above systematically varies along the entire ~100 km length of the western Dead Sea Basin. SE-directed slumping is preserved in the north, easterly-directed slumping in the central portion and NE-directed slumping at the southern end of the Dead Sea. They are interpreted to form part of a large-scale radial slump system directed towards the depocentre of the Dead Sea and to be triggered by earthquakes associated with seismicity along the Dead Sea transform. It is possible to generate a range of 4 overprinting scenarios within a single slump event, with the progressive evolution of slump systems broadly categorised into initiation, translation, cessation, relaxation and compaction phases. Thrust packages typically define piggyback sequences during slump translation, with back-steepening of imbricate faults leading to collapse of folds back up the regional palaeoslope. As deformation intensifies, fold hinges may not always rotate towards the flow direction to create sheath folds, but rather roll downslope to form spiral folds. The identification of cleavages within undoubted sedimentary slump folds, together with distinct cleavage-bedding vergence relationships indicates that the presence or absence of cleavage is not in itself a robust criteria to distinguish tectonic and soft sediment folds. In detail, structural evaluation of slumped horizons may also permit structural linkages to be recognised across apparently separate and distinct slumped units. The recognition that slumps may be reworked by younger seismically triggered events suggests that in some cases the seismic recurrence interval may be shorter than anticipated. The recognition of sheared folds and thrusts verging back up the palaeoslope, and in direct structural continuity with underlying gravity-driven slumps structures, suggests that it is possible to generate up-slope flow of material in some circumstances. The most likely scenario in the present case study are seismically triggered tsunami and seiche waves which would immediately post-date the slump event triggered by the same earthquake.

Relationship Between Topography and Strain-rate in the Actively-Extending Italian Apennines: Evidence of Mantle Involvement in Extension.

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To investigate the mechanism driving active extension in the central and southern Italian Apennines, we compare spatial variations in upper crustal strain-rate measured across exposed fault scarps since 15 ±3 ka with data on cumulative upper-crustal strain and topographic elevation, and free-air gravity, P-wave tomography and SKS splitting delay times that are a proxy for strain in the mantle. High extensional strain-rates across the Apennines since 15 ±3 ka (0.4-3.1 mm/yr along 90 km transects) occur in two areas (Lazio-Abruzzo; SE Campania and Basilicata) where values for finite extensional strains that have developed since 2-3 Ma are highest (2-7 km cumulative throw), and where mean elevation in 5 x 90 km NE-SW boxes is > 600 m; the intervening area (NW Campania and Molise) with < 600 m mean elevation in 5 x 90 km boxes has extension-rates < 0.4 mm/yr and lower values for finite extensional strains (< 2 km cumulative throw). These two areas with high upper-crustal strain-rates overlie mantle that has relatively-long spatially-interpolated SKS delay times indicating relatively-high mantle strains (1.2-1.8 seconds) and free-air gravity values of 140-160 mGals; the intervening area of lower extension-rate has shorter spatially-interpolated SKS delay times of 0.8-1.2 seconds and lower free-air gravity values of 120 mGals. The two areas with high upper crustal strain-rates and strain, mean elevation and mantle strain coincide with the northern and southern edges of a slab window in the Tyrrhenian-Apennines subducting plate that has been inferred from published P-wave tomography. Together these correlations suggest that dynamic support of the topography by mantle flow through the slab window may control the present day upper crustal strain-rate field in the Apennines and the geography of seismic hazard in the region.

Poster Presentation Abstract List

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A lineament study of Southeastern Brazil: insights and limitations

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Lineament analysis is a technique involving the extraction and interpretation of geologic and geomorphic linear features from remote sensed imagery. It can be a valuable tool in gaining insight into the large scale tectonic evolution of a region, and is often used as a reconnaissance tool, prior to more detailed study. We present results from a lineament analysis of the onshore region adjacent to the Santos basin, an obliquely rifted basin whose structures are thought to have been influenced by underlying basement faults and fabrics.

Lineaments were picked from hillshaded SRTM DEM data at a variety of scales and insolation angles, and analysed using both rose diagrams and statistical analyses. A strong NE-SW lineament trend is identified from both analyses, and rose diagrams show compartmentalization of secondary lineament trends, in zones which trend sub-parallel to regional tectonic boundaries.

Whilst lineament trends do appear similar to the trends of structures observed in outcrop, dips of structures may vary, compared with lineaments which are essentially one-dimensional features. It is therefore difficult to make structural interpretations based on lineament analysis alone. Ground-truthing of lineaments in this region is hindered by poor exposure and high levels of erosion. We conclude that any geological conclusions based on lineament analysis must be aware of the limitations of lineament analysis in general.

Combined Rigid/Deformable Plate Tectonic Reconstructions for the Central Atlantic Margins

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Passive continental margins are characterised by a transition zone from continental rifting to oceanic crust accretion. The exact location of the continent-ocean boundary (COB) is often difficult to predict because of the similar physical properties of oceanic crust and highly extended continental crust. Magmatic intrusions have an effect on the calculation of crustal thickness, which adds further uncertainty to the definition of the COB.

The Iberian and Newfoundland conjugate margins are zones which record anomalously large amounts of crustal extension. Within this segment of the Atlantic margins, the formation of continental 'rafts', comprising highly attenuated continental crust, poorly defined oceanic crust and exhumed mantle, is characteristic. The reconstruction of plate boundaries to their pre-extended configurations assuming 'rigid' plate geometries results in large misfits across plate boundaries (e.g. by restoring North America, Iberia, Greenland and Europe Plates, including the Hatton Bank to the Late Jurassic). In order to solve these problems and utilise the information on the amounts of continental extension along passive margins, a new combined rigid/deformable plate kinematic model has been developed, consisting of a complex global chain of rigid plates rotating around a fixed hotspot frame and deformable plates defined along continental margins and within cratonic interiors.

To model the continental deformation, an ArcMap™ extension has been developed (Plate Wizard™). The program creates displacement vector maps that allow restoration of the plate margins by 'warping' the mapped extended regions. The program also allows the restoration of the geometries of geo-referenced datasets that can be intersected with the plates defined by the model.

To date, a self-consistent global, plate tectonic model has been achieved, that incorporates stretching factors and scales deformation for the Cenozoic and Mesozoic for the entire Atlantic margin. Restoration to the pre-rift geometries of the margin in these areas can be refined further by detailed modelling of tectonic evolution and the extent of crustal deformation.

Are Passive Margins Really Passive? The Post-Rift Deformation of the Namibian Passive Margin

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The post-rift evolution of a passive margin is generally considered to be quiescent and controlled by subsidence driven by thermal decay depending on the Mckenzie's simple one-dimensional stretching model and subsequent modified models. A number of recent studies from the NE Atlantic and South Atlantic (e.g. Lundin & Dore, 2002; Paton et al., 2008) have suggested that passive margins may be subjected to significant episodes of tectonic deformation, and this deformation can have an influence on all aspects of the margin evolution including stratal architecture and hence sequence stratigraphy, structural deformation and hydrocarbon prospectivity.

This study aims to examine the effect of post-rift deformation in the Namibian continental margin through an integrated structural-sequence stratigraphic study using 2D seismic data. The Namibian margin represents a typical example for this study because it has a relatively simple structure and lacks the salt deposits found in other sectors of the South Atlantic north of the Walvis Ridge, which makes it is difficult to distinguish between gravity-driven salt tectonics and deformation associated with post-rift margin tectonics.

Depending on the reflection termination patterns (such as onlap, downlap and erosional truncation), three main seismic horizons have been identified across the Namibian margin. These seismic horizons represent major unconformities or their correlative conformities which divided the margin into four megasequences. These megasequences are broadly syn-rift, transitional, and Cretaceous and Tertiary post-rift megasequences.

Isochore maps of the Cretaceous and Tertiary megasequences show that the Namibian margin underwent two main uplift events during the upper Cretaceous and upper Tertiary which affected the inner and middle parts of the margin. Also, the isochore maps show that there was a rapid switching in the location of sedimentation during the Tertiary west of the Cretaceous shelf margin. This switching in the site of sediment accumulation can be attributed to differential margin subsidence induced by margin tilting, and is likely to have increased the maturation of the source rock in the deep-water part of the margin.

The Internal Geometry and Evolution of a Thrust Related Fold in the Deep Water Fold Belt Levant Basin

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Deep water fold and thrust belts are commonly found in association with major gravity deformational systems in passive continental margins. Within these continental margin gravity-driven systems, an up-dip extensional domain is invariably paired with a down-dip contractional domain in which there are assemblages of thrust faults, strike slip faults, normal faults and variety of fault related folds, collectively referred to colloquially as deep water fold belts.

The interactions of thrust faults with strike slip faults, normal faults and other kinds of faults greatly influence the evolution and geometry of the thrust related folds in these deep water fold belts. Understanding the precise nature of the fault interactions is useful in a more fundamental appreciation of the propagation of thrust faults, which in turn is vital for successful hydrocarbon exploration.

This presentation is based on kinematic observations of fault and fold relationships from a high-resolution 3D seismic survey located in the deep water thrust and fold belt of the Levant Basin. The focus of the study is a single fold which changes in geometry systematically along strike. The kinematic data (displacement and shortening strain) suggests that important variations in thrust and fold style relate specifically to positions of interaction with other faults.

We divided the fold into 3 segments along strike, with each segment characterized by a distinctive structural geometry and style. Segment 1- shows various styles of interaction of thrust fault with strike slip faults, Segment 2- depicts vergence reversal of hanging walls and interaction of synthetic and antithetic thrust faults, Segment 3 – Displays thrust faults merging to form a single thrust along strike.

We constructed 3 dimensional throw contour maps of the main thrusts in order to have a 3 dimensional understanding of the interaction of the faults. We suggest that if the main interacting thrust faults do not show similar modes of displacement contours, then their geometries can be attributed to interaction with a series of strike-slip faults and thrust related structures. Models are proposed to explain how the thrusts initiated, propagated and interacted in chronological order. We conclude by discussing the styles of transfer mechanisms in relation to interaction as well as the time of initiation of the main faults.

Comparison of Structural Styles and Hydrocarbon Potential Between the Mexican Ridges and Perdido Fold Belts, Western Gulf of Mexico

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The deep water sector in the western Gulf of Mexico is a frontier area with direct evidence of a significant hydrocarbon potential (e.g. seismic anomalies and multiple sea-floor seeps). It is related to a wide variety of structural styles formed by Tertiary gravity spreading processes affecting the passive margin. The extensional movement on coastal plains, and offshore on the continental and upper slopes is accommodated downdip by compression developing a regional linked system. As a result, major contractional provinces evolved in the deep water areas.

These contractional systems are the Mexican Ridges fold belt, covering the entire western slope of the basin; and the Perdido fold belt, located in ultra deep water around the Mexican and USA international median line. Formation mechanisms and resulting structural geometries in both fold belts are being analysed to understand their evolution and the associated petroleum systems using recently acquired 2D and 3D regional seismic data.

The Mexican Ridges fold belt is a N-S trending Tertiary system that detaches on overpressured Eocene shales and consists of growth symmetric and asymmetric detachment folds related to break-thrust faulting. According to geological and geophysical seismic evidence, deformation started in the middle Miocene and continues to the present time. The Perdido fold belt on the other hand, has a NE-SW contractional trend related to salt-cored detachment folds and break-thrust faults. This contractional system formed above autochthonous Jurassic salt that acted as a detachment level during the late Oligocene to the late Miocene period, and involves a thick Jurassic to Tertiary sedimentary column. These differences are illustrated through cross sections, and a regional seismic line linking both contractional systems.

Although both fold belts have a similar gravity-driven origin, there are notable differences in structural styles associated with the mechanism of folding related to salt or shale tectonics (or both), in areas of juxtaposed or transitional structural styles. Therefore, a comparative structural analysis and detailed seismic interpretation have been made in order to explain geological differences in geometry, detachment levels, faulting and growth geometries, and evolution. This will enable the recognition of the main structural controls on potential hydrocarbon traps in each province.

The Structure, Morphology and Faulting History of the Makran Accretionary Prism

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The Makran, of Pakistan and Iran, is the largest accretionary prism in the world, generated by convergence between the Arabian and Eurasian tectonic plates. It represents an end-member of global subduction zones, with a 7km thick incoming sediment pile. The Makran therefore provides an interesting comparison to other global subduction zones where sediment input is limited or more variable. Until recently the structure of the offshore prism has not been extensively described. 50 industry Multichannel Seismic Reflection (MCS) lines have been interpreted across the offshore Pakistan prism and integrated with swath bathymetry and sidescan sonar data (western region only) to assess the relationship between surface and sub-surface features. Imbricate thrust faults have been correlated across the margin, producing a structure map which shows a series of overlapping, landward dipping fault segments of 20-160km in length. The geomorphology of the prism is controlled by thrust ridges, and significant submarine canyon-channel systems which transport sediment to the trench. The top of the oceanic basaltic layer can be traced beneath the prism. Basement depth increases along the trench from east to west with significant local topography in the east. The NE-SW trending Murray Ridge, which blocks sediment transport from the Indus Fan to the north, and Little Murray Ridge are visible. There is widespread evidence for fluids, with a strong BSR (bottom simulating reflector) present throughout the prism, indicating the presence of free gas overlain by gas hydrate.

Fault spacing across the prism is generally consistent at 3-7km. Fault spacing increases locally over the Little Murray Ridge to 18km. It is possible to asses the relative displacement and activity of the thrust faults in space and time by interpreting the geometry of piggy-back basin stratigraphy between individual thrust slices. Wedge shaped sediment packages indicate syn-sedimentary, landward tilting of basins. Thrust faults can be categorised according to their relative activity through time, and their recent activity. The majority of faults show intermittent or continuous activity, with only a small percentage appearing to be largely inactive. In some cases it is possible to follow the piggy-back basin for a specific thrust along strike, allowing fault activity along strike to be investigated. Variations in activity from the prism toe to back can also be assessed. In addition specific horizons have been picked and correlated across the frontal thrust to provide a 'semi-quantitative' interpretation of activity and displacement through time.

Rheology and Flexure in the Rockall Trough: New Insights from Numerical Modelling

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The Rockall Basin is the dominant bathymetric and geological feature of the UK-Irish Sector of the North-East Atlantic margin, but it remains poorly understood. For example, there is still debate about the timing of the subsidence and uplift events that led to its formation, the rheological properties of the lithosphere beneath it and the causes of the unconformities observed within and around it.

A quantitative study of the rheological strength of the lithosphere during the evolution of the Rockall Trough has been undertaken, focusing on differences between the northern and southern parts of the basin which are separated by the Anton Dohrn Lineament System. Results from this modelling-based study show the importance of the thermal anomaly generated by the Icelandic Hotspot and its influence in the northern Rockall Trough in contrast to the relatively unaffected southern Rockall Trough.

Model results show that the change in rheological strength over time does play an important role in the evolution of the Rockall Trough and can account for some differences observed between the northern and southern sub-basins. In particular, the northern and southern parts of the basin may represent different stages in the extension process, with the more advanced extension in the south allowing ingress of sea-water to upper-mantle levels, modifying lithospheric rheology and subsequent deformation style. Additionally, it is likely that extension rate has influenced the evolution of the basin with cooling and strengthening during slow extension, leading to the migration of deformation away from the basin axis and towards its margins.

Geomechanical Impact of CO_2 Injection on low Porosity Storage Domain Rocks (Caprocks and Barriers to Fluid Flow): an Experimental and Analytical Approach

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Field trials into CO_2 sequestration are currently being undertaken at In Salah, Algeria. As a part of a wider project, we are investigating the geomechanical and geochemical effects of CO_2 storage on the caprock to the host reservoir. Here we present initial results on the geomechanical effects of fluid injection on both the caprock and a typical reservoir sandstone.

Detailed experimental studies of the development of permeability in storage domain rocks during deformation are essential to understand the integrity of both the borehole and caprock on short term timescales during injection of CO_2 to help constrain larger-scale models that predict bulk fluid flow within the storage system. It has been demonstrated from experiments and modelling that accumulation of microfractures under differential stress before rock failure occurs systematically and leads to enhanced porosity, permeability and fracture surface area. Changes in stress affecting storage domain rocks can occur on short-term production timescales from (1) drilling boreholes, which will change the stress field and lead to greater differential stresses, bringing the rocks closer to failure and potentially increasing permeability, and (2) from injection of CO_2, where increasing pore fluid pressure will reduce the effective stress, bringing the rocks closer to failure and potentially increasing permeability.

We present results from direct experimental evaluation of permeability evolution for both these situations of changing stress conditions on samples of low porosity rock from the In Salah CO_2 storage site, representing a barrier to fluid flow, and samples of a sandstone representing a porous reservoir rock. Stress changes were found to cause pre-failure permeability increase of up to two orders of magnitude in the low-porosity In Salah samples, and up to one order of magnitude for the sandstone. These results illustrate the need for care while injecting CO_2 into the subsurface even at pressures well below the hydrofracture limit.

Predicting Sub-surface Fracture Networks from Modelled Stresses and Strain – how well can it Replicate Natural Fractures?

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Fracture networks have an almost ubiquitous presence in petroleum reservoirs, as well as CO_2 storage sites, but understanding the distribution, orientation, and stability of those fractures is pivotal to assessing whether a reservoir will produce effectively, or if CO_2 will remain contained. Our study utilises a stochastic approach to sub-surface fracture prediction, using modelled stress and strain across a sub-surface model, to predict the fracture network. Andersonian principles have been used to control the orientation of the fractures modelled. These predicted fractures are then compared with available well and pressure data to assess how well the fracture orientations mimic those observed in nature.

The fracture modelling was completed on a low-amplitude anticline cut by minor, predominantly strike-slip, faults. The surface was restored using both geometric and geomechanical algorithms and then forward modelled to predict the spatial distribution and intensity of stresses and strains through time. The strain associated with the faulting and folding was captured in different increments to allow differentiation between possible fracture-sets.

The modelled discrete fracture networks (DFNs) used the captured strain magnitude as a proxy for fracture intensity, and fracture orientations were derived from the orientations of the principal strain axes and stress orientations by applying an Andersonian model for rock failure in relation to the principal stresses. Multiple fracture sets were generated, utilising the two increments of strain associated with the faulting and folding of the reservoir. The generated fracture networks were then compared with observed data collected in FMI well logs, to assess how well the modelled DFNs correlate with the real data.

A further step in the modelling workflow is to assess the stability of the fracture networks under present-day and paleo-stress conditions and varying pore fluid pressures. This stability analysis allows prediction of open fractures and their connectivity to predict 'open' pathways (where fractures are in extensional or shear failure and connected). This provides a further QC of the modelled DFN with real fracture networks by comparing the predicted 'open' pathways with known flow pathways derived from well pressure data. Knowledge of whether the existing fracture networks are close to critical failure (under shear or tension) is crucial to understanding how a reservoir may react during production, or whether the fractures will withstand the injected CO_2 pressures.

The Three-Dimensional Geometry and Kinematics of Brittle Structures in the Immediate Hanging-Wall of Large Extensional Faults: Implications for Sub-Surface Hydrocarbon Migration and Entrapment

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In the past few years, the focus of research into the effects of faults on hydrocarbon migration has shifted from the study of single faults to encompass the geometrical relationships between spatially limited but kinematically linked faults, and the effects that structures such as deformation bands at tip points, relay ramps and fault linkages may have on migration. Such structures have been shown to strongly influence subsurface hydrocarbon migration, but form at a scale which is not resolvable on seismic, and hence they are not currently taken into account when modeling potential hydrocarbon traps and migration pathways.

This study examines the structural geometry and detail of a number of sub-seismic scale, en-echelon fault segments and their related brittle deformation structures that are well exposed within the hanging-wall rollover of a large, seismic-scale extensional fault within the Cache Valley, Arches National Park, Utah, U.S.A. Detailed structural mapping has been carried out through field survey, supported by analysis of high-resolution satellite imagery, and is used to develop a series of cross-sections which form the basis of a three-dimensional structural model of the fault system. Structure-frequency data are used in conjunction with kinematic modeling to investigate the relative distribution of surface strain and its relationships to sub-seismic scale brittle deformation structures across the exposed relay ramps.

The fault system is shown to be highly compartmentalised, with complex, interacting damage zone geometries containing brittle deformation structures that together have the potential to result in small, isolated trapping structures and distributed migration pathways. Moreover, the en-echelon fault geometry of the rollover can be linked to a variation in displacement on the controlling fault along strike. Since displacement on faults of this scale is resolvable and can be recognised on seismic, it follows that sub-seismic scale, brittle deformation structures within the hanging-wall rollover, and their potential implications for hydrocarbon migration and entrapment may be predictable based on the displacement gradient on the controlling fault.

This model is applied to the hanging-wall rollover of a large extensional fault that is well imaged on seismic from the Offshore Falkland Islands, and shows a clear displacement gradient, in order to predict the effects of sub-seismic scale brittle deformation structures on possible migration and entrapment of hydrocarbons within this structure.

Patterns in the Locations and Characteristics of Natural CO_2 Seeps in Italy

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Italy is a region of anomalously high natural CO_2 degassing; it is estimated that over 5.3 Mt/yr of CO_2 is released through the crust from ~ 300 known terrestrial CO_2 seeps. These seeps exhibit a range of characteristics, with a variety of surface expressions, flux, compositions, and temperatures and can relate to travertine (continental carbonate) formation. Carbon isotope studies on these gases reflect a mixed origin; with varying proportions of mantle, crustal and biogenic sources.

There are clear broad-scale controls on seep distribution which reflect both deep processes and regional tectonics. Seeps concentrate in the western sector of Central and Southern Italy where the lithosphere is significantly thinned in comparison to the Eastern sector. CO_2 flux is much reduced in the Apennines, Italy's seismic belt, where unusual aftershock sequences have been attributed to the presence of trapped CO_2 fluids at depth. Within internal Central and Southern Italy, hydrocarbon exploration drilling frequently encountered CO_2 accumulations in reservoirs formed from flysch-topped thrust nappes. Some reservoirs are geographically related to CO_2 seeps which might imply breaching of the reservoir seal, or "leaky" reservoirs, analogous to leakage scenarios from engineered CO2 storage sites.

On a local scale, it is well known that faults control crustal fluid flow and the hydrogeological system. Indeed, springs in faulted environments are typically located at fault tips, regions of fault link-up (linkage, bifurcation etc) or along fault surface traces. It is expected that both wet and dry CO_2 seeps and travertine follow this fault association. The nature of the seep-hosting lithology is also expected to influence CO_2 seep expression and characteristics.

CO_2 gas seep, exploration and tectonic data allow us to identify and quantify the key patterns in the distribution and characteristics of CO_2 seeps using geostatistical methods. With this we elicit the controls on count density and flux of CO_2 fluids and their surface manifestations on both local and regional scales. The results are very interesting, and reflect the nature of CO_2 fluid flow pathways in a range of geological circumstance.

This research forms part of a PhD project which aims to better understand the plumbing of CO_2 fluids in the Earth's crust and model the architecture of CO_2 migration from complex seal reservoirs thereby guiding legislation for geological CO_2 disposal.

Using a Sequential Indicator Simulation to Model Fluid Flow Connectivity Across Faults: an Approach Using Simple Artificial Geocellular Models

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Fault zone architecture, defined as the three-dimensional spatial arrangement of petrophysical elements (e.g. zones of gouge or cataclasite, lenses of wall rock, and fringing damage zones) is highly spatially variable across a fault surface. This inevitably leads to heterogeneity in the fluid-flow properties of the fault zone. However, the implementation of faults in geocellular models typically simplifies this complexity by modeling a fault as a single plane, and ascribing a transmissibility multiplier to it. Volumetric modeling of fault zones, to capture the range of possible fluid flow behaviours across a fault, is still a relatively novel approach.

We use simple artificial geocellular models, constructed using Petrel, to illustrate the influence that variations in fault architecture have on cross-fault and along-fault connectivity of sand bodies. Two models were constructed. The first model contains a simple fault plane juxtaposing strata consisting of alternating sand and shale layers, each of which is 20 m thick. The model is set up such that there is no connectivity between sand units across the fault. The second model is similar, except that the fault zone has a constant thickness of 10 m, and contains sand and shale stochastically distributed according to a Sequential Indicator Simulation (SIS). The proportions of sand and shale were varied (50%, 75% and 90% shale), and an SIS was run for variogram range values of 50 m and 10 m for each proportion. Five realisations were completed for each combination of shale proportion and variogram range. The “connected volumes” property in Petrel was then used to visualise how sand bodies were connected to each other across the fault for each realisation. For 50% and 75% shale, all sand bodies are typically connected to each other across the fault, regardless of variogram range. For 90% shale and 50 m range, there is typically connectivity between sand bodies on the same side of the fault, but no connectivity across the fault. For 10 m range, there is no connectivity between any of the sand units. We suggest that a volumetric approach may more realistically model fluid flow through faults, where flow both across and along the fault can simulated. To further explore the influence of fault architecture on fluid flow in geocellular models, we propose a forward-modeling approach to create geometrically realistic faulted volumes. These volumes can be stochastically populated with different architectural elements, used as test beds to examine the influence of different parameters, including architecture and fault content.

Seismic Imaging of Methane Hydrates, Offshore of Mauritania

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Below a few hundred meters of burial, gas hydrate becomes unstable and gas and water exist in a free gas zone (FGZ). The base of the gas hydrate stability zone (BHSZ) is commonly marked by a high amplitude seismic reflection that is parallel to the seabed but has the opposite polarity. Rather than venting to the seabed, dissociation of gas hydrate can be stored in the FGZ which is sealed by the hydrate. Many FGZs are thought to be critically pressured, so any additional free gas could be sufficient to reactivate faults within the hydrate, allowing methane release to the seabed. Methane may be repetitively recycled between the hydrate and the FGZ by upward and downward resetting of the BHSZ (known as hydrate recycling). However, dissociated gas could also be stored in stratigraphic traps sealed by surrounding low-permeability sediment.

We describe seismic reflection data from a world-class example of a gas hydrate reservoir offshore of Mauritania. The BHSZ reflection shallows with reducing water depth and intersects the seabed. There are also hundreds of vertical chimneys, which are indicative of methane migration from critically charged free gas reservoirs below the hydrate. There is very little evidence for methane leak to the surface, but it does occur where there are through-going faults which cut through the hydrate. These faults are permeable to gas and vents are aligned on the seabed. The aim of the project is to provide the capability to discriminate between gas trapped at the base of the hydrate (i.e. the FGZ) and free gas sealed stratigraphically by surrounding low-permeability sediment. Furthermore we aim to understand how methane is stored and leaks to the seabed.

Dextral strike-slip shearing associated with melt emplacement in a ductile thrust system, Torrisdale, Scotland

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In north Sutherland, the granites and pegmatites of the Torrisdale Vein Complex occur above the Naver Thrust and form sub-vertical intrusions that vary from veins a few cm thick to large sheet-like bodies up to 100m thick. Intrusions cross-cut both D_2 and D_3 folds, although relationships are complicated by overprinting during development of the D_4 Torrisdale Steep Belt. During D_4, intrusions that were oriented at clockwise angles relative to the regional fabric were commonly folded, whereas those at anticlockwise angles were asymmetrically boudinaged, indicating dextral senses of shear parallel to L_4. In detail, folded pegmatites are typically developed ~10° clockwise of the mylonitic foliation (trending ~150°) and form steeply plunging "Z" folds. Folded pegmatites may display boudinage on their limbs suggesting that boudinage developed after folding, when the pegmatite had entered the extensional field during progressive deformation. Pegmatites typically form parallel (Type 1B) folds and were more competent than their host grey gneisses and amphibolites at the time of deformation i.e. pegmatites were not in the magmatic state. However, folded pegmatites occasionally display pronounced thickening and thinning on their limbs suggesting extreme ductility. Boudinaged pegmatites are typically developed ~10° anticlockwise of the mylonitic foliation and form individual boudin trains traceable for 10's of metres. Within such trains, individual boudins are rotated less (i.e. are more anti-clockwise) than the overall train and show right-stepping relative to neighbouring bodies. Some boudins display flanking folds and local reversals in the sense of shear consistent with a clockwise vorticity associated with bulk dextral shear. Most pegmatites occur where the Naver and Torrisdale Thrusts have an NW-SE sub-vertical orientation along the North coast, which is anomalous compared to the gentle-moderate E-directed regional dips. This may reflect 2 basic models associated with 1) extrusion of underlying nappes towards the west generating a relative top-to-the East shear that is accommodated in the steep NW-SE trending Torrisdale rocks by dextral shear. Alternatively, 2) Torrisdale may form part of a domino fault system associated with a transfer zone located off the N coast. Regional top to the west shear would create dextral dominos as observed at Torrisdale.

The "Canaã dos Carajás" region, a limit between the Carajás and Rio Maria Granite Greenstone terranes

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In the Amazon Craton, there are two important Archaean regions that record geological events ranging from 2.9 to 1.8 Ga: the Rio Maria Granite Greenstone Terrane and the Carajás Ridge. The first shows a dominance of vertical tectonics, whilst horizontal-to-oblique tectonics predominate in the second. The limit between these tectonic units has been a topic of discussion for several decades. This study presents geophysical, microstructural and field-based data from the granitic-gneissic basement, in the boundary between these terranes, known as the Canaã dos Carajás region. The studied rocks comprises Archaean TTG gneisses, lens shaped amphibolite bodies, 2.7 Ga. syntectonic alkali granitoids and 1.88 Ga. isotropic granites. These rocks display widespread heterogeneous, anastomosing WNW-ESE and NE-SW foliation sets related to steeply-dipping ductile shear zones associated with steep-to-moderately plunging mineral lineations. The nature and geometry of the ductile fabrics are compatible with a bulk pure-shear dominated transpression with shortening and extensional directions oriented at approximately near horizontal (~020° Az) and near vertical respectively. Microstructures in quartz and feldspar indicate deformation at metamorphic conditions compatible with middle to upper amphibolite facies (~650-700°C), overprinted by deformation at middle to upper greenschist facies conditions (~400-500°C). The magnetic and radiometric surveys indicate a prominent sinuous E-W trending anomaly 20km wide and hundreds of kilometers long that cross-cuts the area. This structure is likely to be a regional scale shear zone and is associated E-W elliptical features that are likely to represent granitoid plutons. The Archaean rocks in the region of Canaã dos Carajás, near to the boundary between the Carajás and Rio Maria Granite-Greenstone terranes, are interpreted to represent part of an original granite-greenstone terrane that has undergone substantial reworking during a later regional transpressional deformation. This reworking records a temporal change from vertical tectonics, which formed the granite greenstone terrane, to a more horizontal-dominated tectonics regime at c.a. 2.7 Ga. during sinistral transpression accompanied by widespread syn-tectonic sub-alkaline magmatism.

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The Role of Tectonic Structures in the development of Archaean IOCG Deposits: Examples from the Sossego and Sequeirinho Deposits, Carajás, Brazil

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This study outlines the structural setting and mineralization controls on the IOCG (Iron Oxide Copper-Gold) deposits of Sossego and Sequeirinho in the Carajás area of Brazil. Sossego comprises a sub-circular, vertical, pipe-like orebody with a central breccia surrounded by a stockwork array of sulphide veins, faults and shear zones hosted by a granophyre intrusion. The granite shows an anastomosing, WNW-ESE trending foliation with moderate NE dips, cross-cut by sub-vertical, poly-directional and mutually cross-cutting faults, veins and shear bands in the stockwork zone. Tensile and shear veins show single or composite mineral fillings consistent with episodic vein opening. The Sossego breccias show angular fragments formed by fracturing and cracking assisted by highly pressurized fluids. Sequeirinho is an asymmetric “S” shaped orebody where: (1) the ends are hosted by schists and granitoids with sub-vertical anastomosing WNW-ESE regional foliation; (2) the central part linking the “S” tips, comprises mineralized breccias developed in a NE-SW shear or fault zone. Thus the early WNW-ESW ductile fabric is offset by a sinistral NE-SW fault zone that hosts the main sulphide breccia body. The early regional foliation is accompanied by a down-dip mineral lineation, resulting from the action of near horizontal shortening component, linked to a vertical stretching component. WNW-ESE mylonitic zones mark narrow domains of intense strain accumulation. Sequeirinho breccias clasts are sub-rounded to rounded formed by wear and attrition of particles consistent with episodic slip along a fault zone. Microstructural observations of quartz and feldspar indicate that the deformation at Sossego and Sequeirinho initially took place under low-to-middle (300-400°C) and middle-to-upper (400-500°C) greenschist facies, respectively. The early fabrics were then overprinted by late brittle-ductile structures and veins containing the main copper mineralization and lower-temperature minerals (170-250°C). The findings suggest that deformation and mineralization took place at 2.7-2.6 Ga. under regional sinistral transpression. Mineralization appears to have formed during the late stages or shortly after the transpressional event, under a semi-brittle to brittle regime and was probably linked to the major thermotectonic event. The interplay between deformation metamorphism-magmatism provided the source metals, transporting fluids and created the structures where the mineralization became trapped.

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Tectonic Problems in the Higher Himalayan Shear Zone, Bhagirathi Section, Indian Himalaya

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Channel flow has been among the mechanisms proposed for the extrusion in different sections of the Higher Himalayan Shear Zone (HHSZ). A review of these mechanisms reveals that none of them account for the Bhagirathi section of the HHSZ in the Garhwal Indian Himalaya. The Garhwal Himalaya is characterized by *(i)* the Main Central Thrust (MCT) activated around 19.8 ± 2.6 Ma; *(ii)* a pressure gradient in the MCT zone of 0.6 to 1.2 kb km^{-1}; (*iii)* three phases of folding in the MCT zone; *(iv)* a local pure shear to simple shear ratio that so far has remained indeterminate; *(v)* vigorous chemical weathering; and *(vi)* the middle of the HHSZ extruded at a rate of ~ 0.67 ± 0.13 mm yr^{-1}. Gaps in knowledge include *(i)* the lower boundary of the extensional Malari Fault has not yet been demarcated; and *(ii)* the tectonic status of the Jhala Fault remains equivocal- is it a thrust or thrust followed by a normal fault? Some other questions are: *(i)* what is the spatial extent of extensional shearing in this section of the HHSZ? *(ii)* Where are the South Tibetan Detachment System-Upper ($STDS_U$) and the South Tibetan Detachment System-Lower ($STDS_L$)? *(iii)* And finally, can channel flow be a suitable extrusion model for the HHSZ in the Garhwal Himalaya?

Structure and Damage Patterns of a Seismic Fault Zone

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Fault zone structure over a wide range of scales strongly influences earthquake mechanics. We present results from an ongoing project that aims to quantify the structure and fracture network characteristics of the seismic Gole Larghe Fault Zone (GLFZ) in the Italian Alps, exhumed from 8-10km depth. The GLFZ is c.500m thick and accommodates a total displacement of c.1000m, distributed amongst hundreds of first- and second-order oblique-slip cataclasite- and pseudotachylyte-bearing faults. The faults nucleated on pre-existing joints in granitoids of the Adamello batholith. Due to the continuous, glacier-polished nature of the exposures, we are using a range of digital mapping techniques, together with sample collection, to survey the fault at scales of centimetres to kilometres. The main results to date are: 1) Joints outside the GLFZ formed predominantly at temperatures >500°C, whilst cataclasite- and pseudotachylyte-bearing fault strands within the GLFZ were active at 200-300°C. The transition from jointed 'wall rock' to 'fault zone' is marked by an *abrupt* increase in macroscopic fracture density; 2) Second-order faults inside the GLFZ are strongly clustered around first-order faults. However, in around 70% of cases, second-order faults are *asymmetrically* distributed on the northern side of first-order faults. This damage asymmetry is not explained by lithological variation, but may reflect the fact that propagating earthquake ruptures preferentially follow one of the boundaries between a pre-existing joint cluster and relatively intact host rock; 3) P-wave velocities measured on 37 samples collected along a c.300m profile across the wall rock and fault zone *increase* from 3500-4500m/s in the wall rock to 5000-6000m/s inside the fault zone. We suggest that the increase in P-wave velocity may reflect sealing of pervasive microcracks by minerals such as epidote and K-feldspar; future work will quantify microcrack densities and fills. The above field observations suggest that the GLFZ is markedly different from other seismic fault zones, where fracture density increases exponentially towards the fault zone and P-wave velocities decrease from the wall rocks towards the fault zone.

The Age, Geological Character and Structural Setting of Quartz-Pyrite Veins in the Assynt Terrane, Lewisian Complex, NW Scotland

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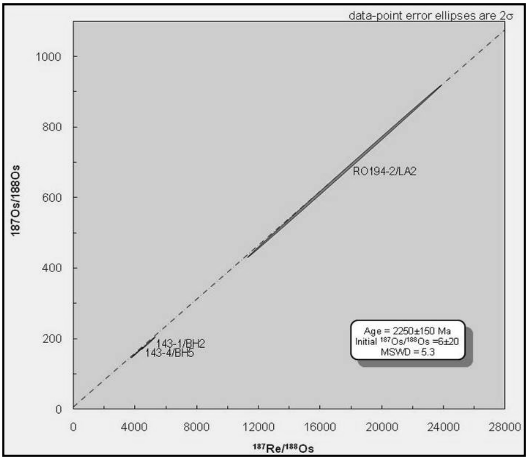
A set of previously unrecognised quartz-pyrite veins are present in the Assynt Terrane of the mainland Lewisian Complex, northwest Scotland. The veins cross-cut early (ca. 2.9-2.8 Ga) Badcallian gneissose fabrics and (ca. 2.4 Ga) Scourie dykes in the Lewisian, as well early pre-dyke fabrics related to the Inverian shearing event. The veins have been reworked by Laxfordian deformation fabrics (ca. 1.8 Ga) and by later brittle faults of various ages. Preliminary analysis suggests the veins are in a multi-modal system which may, in places, have been influenced by the existing foliation of the gneisses, although there is a trend towards northwest-southeast extension. Pilot dating of three samples of pyrite present within the veins, using the Rhenium – Osmium (Re-Os) geochronometer, give ages of ~2.2Ga, confirming the regional chronology and providing the first reliable constraint for the Inverian, the main shear zone forming event in the Lewisian Complex. Further dating hopes to confine this further. A microstructural study of the veins will provide constraints on the P-T conditions at emplacement and during subsequent overprinting events. This project hopes to provide important new insights into the application of terrane models to ancient orogenic complexes and potentially to recognise a signature event which is restricted only to the Assynt Terrane.



A Reinterpretation of Clastic Intrusions and Infills in Basement Gneisses at Clachtoll, NW Scottish Highlands

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Clastic sediments along fractures in Lewisian gneisses at Clachtoll, NW Scotland, have previously been used to determine the age of fault movements, as well as infer the regional stress orientation during faulting. In particular, the 'Clachtoll Fault Zone' ('CFZ') has been interpreted as accommodating WNW-ESE extension during a regionally recognized Stoer Group-age intracontinental rifting event. Here we present new evidence that indicates the 'CFZ' does not exist and that the observed fracturing is related to the gravity-driven emplacement of a large (>150,000 m^3) clast of basement gneiss into the basal Stoer Group.

The Lewisian basement at Clahtoll forms part of the Canisp Shear Zone and is dominated by amphibolite-facies acid and mafic gneisses that typically display a well-defined steeply-dipping WNW-ESE-striking foliation, resulting from superimposed Inverian and Laxfordian transpression events. The 'CFZ' is associated with a section of basement where foliation strikes NNE-SSW (i.e. at 90° to the strike of the surrounding Canisp Shear Zone), which is highly fragmented. Fragmentation increases markedly eastwards, and with it, the volume of clastic sediment. Sediment fills along fractures are either massive or bedded muddy sandstones that link together vertically and laterally. Bedded fills dominate towards the top of the exposure and indicate gravitational sedimentary deposition. Massive fills are dominant in the lower exposures, and forma complex network of interlinked extension and extensional-shear fractures that locally support cm- to dm-size blocks of gneiss. These massive sands are interpreted as clastic intrusions.

Fault slip magnitudes, breccia characterization and clastic intrusion geometries indicate that the region of gneiss with NNE-SSW foliations was not rotated by faulting, but rather that it was deposited, probably during slope failure. It therefore represents a very large (fragmented) clast within the Stoer Group. Offsets of gneiss foliations across clatic intrusions show that local extension directions were highly variable, and markedly inconsistent between adjacent fractures. This favours elevated pore fluid pressure – probably created during gravity-driven emplacement of the block into wet sediment – rather than tectonic stress as the cause of internal faulting. Whilst the slope failure process envisaged here was broadly associated with the development of a rift-related fault scarp, the so-called 'CFZ' and associated structures cannot be used as a palaeostress indicator for rift events.

What can seismic anisotropy tell us about ice deformation?

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Seismic anisotropy is a well-established technique for probing deformation in the solid Earth and is known to be influenced significantly by patterns of crystallographic preferred orientation (CPO) of elastically anisotropic rock-forming minerals. As ice is also elastically anisotropic it too can be expected to exhibit seismic anisotropy. Due to its hexagonal crystal structure, a single crystal of ice has a concentric anisotropy distribution about the crystallographic c-axis, so-called vertical transverse isotropy (VTI). The minimum in anisotropy (<1%) occurs parallel to the VTI axis, whilst the maximum (~15%) occurs in a concentric ring at ~45° to this axis. In contrast, polycrystalline ice exhibits three distinct c-axes CPO: 1. random; 2. clustered about the VTI axis; and 3. girdle through the VTI axis. Both clustered and girdle CPO are caused by deformation. All three CPO are responsible for characteristic modifications of the single crystal ice seismic anisotropy distribution. Random CPO reduce significantly the anisotropy for all orientations, typically to only 1 – 2%, although weak VTI patterns may remain recognisable. Clustered and girdle CPO also reduce the single crystal anisotropy but values remain significant (i.e. 5 – 10%). Furthermore, whilst the former maintain the basic VTI pattern, the latter are responsible for modifications depending on the intensity of the c-axes girdle distribution. The implications of these CPO differences for natural ice are significant. Clustered CPO tend to be oriented (sub-) vertically and hence vertically propagating seismic waves sample the lowest anisotropy values. Girdle CPO also tend to be (sub-) vertical but in this case vertically propagating seismic waves may sample somewhat higher anisotropy, although still considerably less than the maximum possible. Furthermore, whilst c-axes girdle CPO appear to develop normal to the direction of ice flow, the VTI symmetry of c-axes cluster CPO fails to recognise this direction (unless the flow is radial). The direction of ice flow is indicated also by the maximum in P-wave velocity and the dominant concentration of crystal a-axes, whilst the fast shear waves that propagate parallel to c-axes girdles are polarised normal to this direction. These results have significant relevance for the interpretation of natural seismicity of ice. For example, observations based on vertically propagating seismic waves from sources directly beneath a receiver are unlikely to reveal sufficient information. Rather, wider (up to 50 - 60°?) angles of incidence are required, such as those provided by seismic reflection surveys from passive sources. Examples of random, cluster and girdle ice c-axes CPO and the associated seismic anisotropy are provided from the Vostok ice core (Eastern Antarctic Ice Sheet).

A Scaling Analysis of a Strike-slip Fault Network Offshore Hartland Point, North Devon

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A strike-slip fault network offshore Hartland Point has been investigated with the objective of determining the geometry, kinematics, strain and scaling. The network comprises NW-trending right-lateral faults and NE-trending left-lateral faults that cut steeply dipping (~60°) and folded Upper Carboniferous strata. The strike-slip fault network was mapped from multibeam bathymetry coverage of the offshore region to the west and north of Hartland Point. Lateral separations of marker beds and fold axial traces were measured along fault traces and correlated with onshore field mapping at Hartland Quay, which confirmed the lateral movement of the strike-slip fault sets.

The fault network is dominated by right-lateral faults (79%) with the larger faults ranging from 10-146 m in displacement making up ~30% of the cumulative fault trace length throughout the study area. This, combined with an anticlockwise rotation of stratigraphy, suggests the strike-slip fault network is acting in a right-lateral domino fashion. Strain analysis shows that the area has a maximum extension of 3.98% in a WNW-ESE orientation. Even though most of the fault trace length is taken up by smaller faults, 84% of the overall extension is accumulated by on faults with >10m displacement and ~50% by faults with >40m displacement. The connectivity of the network is analyzed in terms of a system of fault branches between tips (I-nodes) or intersections (X or Y-nodes). The percentage of fault branches ending at Y- or X-nodes increases with inclusion of smaller faults (<10m) within the system. This is related to the nature of interacting Y- and X- shaped nodes. Synthetic Y-shaped nodes are dominant for faults with >10 m displacement, whereas for faults with <5m displacement, antithetic Y-shaped nodes dominate and X-shaped nodes are introduced. This, combined with an increase in fault density from 2.5km^{-1} to 5.7km^{-1}, indicates that connectivity is reliant on small faults.

Thus, we are able to show that strain within this fault network is localized on the larger faults which take up most of the rotation of the domino system. However, small faults play an important role in linking faults providing the connectivity within the network. This work forms part of a wider study aimed at understanding distribution and organization of displacement and damage within fault networks.

Miocene Tectonics and Deep Marine Sedimentation in the Southwestern Gulf of Mexico

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The study area comprises two 3D seismic surveys recently acquired offshore in Mexican waters of the southwestern Gulf of Mexico. This area covers a surface area of about 17,000 km^2 with bathymetries ranging up to 2500m depth. Geologically, this area includes three provinces from east to west: Cuenca Salina Sur, Catemaco Thrust & Fold Belt and the Mexican Ridges. The prediction of deep water reservoirs in complex tectonic settings represents a major challenge and this research is therefore focused on unraveling the tectono-sedimentary evolution of one such area. A sequence of tectonic events occurred during the Miocene that included orogenic contraction, gravity-driven contraction and salt tectonics. In addition, arc and intraplate magmatism were also active during this time. As a result, deep marine sedimentation in this portion of the Gulf was strongly influenced by deformation and volcanism. The lower Miocene is composed of a thick sequence of debris flow deposits and turbidites that were deposited in slope and basin floor environments. Lithologically, this stratigraphic level is composed of lithic sandstones, conglomerates, conglomeratic sandstones, siltstones and mudstone. The high content of clastics derived from volcanic, plutonic, metamorphic and older sedimentary rocks indicates multiple sources of provenance. These clastics were derived from the intense erosion of uplifted continental blocks, arc-related volcanic terrains and the Laramide deformational front. The middle Miocene is made up of clastic rocks similar to those deposited during early Miocene. However, these deep marine sequences were syn-tectonically deposited in a confined environment created by contraction of the Chiapaneca Orogeny. Furthermore, this orogenic event also reactivated halokinesis in the Cuenca Salina Sur; as a result, sedimentation was confined to minibasins and synclines. Finally, the upper Miocene represents the syn-tectonic fill of synclines in the Catemaco Thrust Fold Belt. Likewise, this stratigraphic level represents the syntectonic fill of the synclines in the Mexican Ridges. In contrast, an unconfined channel complex system was developed along the undeformed corridor formed between these two fold belts. The sources for this deep water clastic system changed significantly due to the beginning of the alkaline basaltic volcanism in the Los Tuxtlas and Anegada volcanic centers.

Velocity Structure of the Carboneras Fault Zone, S.E. Spain

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The Carboneras fault, SE Spain, is an exceptionally well-exposed, large offset strike-slip fault. The rock products of faulting presently seen were formed at 3-5 km depth, on the basis of deformation mechanisms and clay mineralogy developed from the breakdown of feldspars and micas of the metamorphic basement rocks. Structural characteristics observed and the mechanical characteristics inferred from laboratory work can be compared to observations of the San Andreas fault at the SAFOD drilling site around Parkfield, CA. Similarities suggest that the structures seen in the Carboneras fault may be analogous to the San Andreas fault at corresponding depths.

It is widely held that upper crustal fault zones consist of a number of fundamental components: fault core, damage zone and protolith. Conceptual fault zone structure models describe only the end-member fault structures, with an array of fault zone structures existing between them. The structure of the Carboneras fault is best described as dominated by anastomising strands of clay-bearing fault gouge, chiefly derived from graphite mica schist and phyllites, enclosing lenticular slivers of damaged rock. Such distributed deformation is usually produced by strain hardening and/or velocity hardening deformation characteristics.

We have measured acoustic wave velocities of a representative suite of rocks of the Carboneras fault zone, to aid interpretation of in-situ high-resolution seismic refraction and reflections studies. Velocities were measured on intact samples over a range of pressures. At low pressures velocities are strongly pressure sensitive, until sufficient pressure is applied to close cracks and/or collapse pores. Pore volumometry was used to track changes in porosity during pressurization cycles and volume corrections applied to high porosity dry rocks. At any given pressure, the range of rock types present exhibits dry compressional wave velocities ranging from 1.154 to 6.681 km/s. The slowest rocks are the clay-bearing fault gouges, that display unusual behaviour that suggests a large fraction of collapsible pore space recovers elastically upon depressurization. The behaviour is comparable to graphite.

The small samples used in laboratory tests cannot capture the overall density of long cracks that are present in the damage zones in and around the fault zone. Using previously published theoretical analyses, we have attempted to estimate corrections to be applied to the laboratory-measured velocities to take into account crack damage. In this way it has proved possible to reconcile laboratory and in-situ seismic estimations of velocities, the first step towards modeling the seismic structure of the fault zone by combining the results of field geological mapping with the laboratory velocity measurements.

Deep Reflection Seismic and the Virtual Seismic Atlas

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The Virtual Seismic Atlas (www.seismicatlas.org) hosts a number of images from vintage and recent deep crustal reflection seismic studies. Deep reflection seismic data give unparalleled insights into the structure of the lithosphere that cannot be obtained by other means. Constantly improving acquisition, processing and filtering techniques help in extracting more information from new and old seismic surveys. Due to the improving techniques, seismic reflection imaging of the basement is becoming increasingly important in ore exploration and for societal aspects, specifically for planning repositories for spent nuclear fuel.

On the VSA, many images from the vintage BIRPS surveys are shown side by side with examples displaying the improvements in the seismic imaging that can be achieved by filtering and/or reprocessing techniques. Other examples, such as the FIRE project (Finnish Reflection Experiment) show how a resolution of few tens of meters throughout the crust can be achieved with modern acquisition methods. The FIRE data is used in a project studying the behaviour of a mountain belt at the late stages of an orogeny, specifically the processes involved in the syn-orogenic extension and mid-crustal flow. Examples are also shown from a HIRE (High Resolution deep reflection seismic) survey by Posiva (www.posiva.fi), displaying how seismic reflection data can be utilized in the planning of a nuclear waster repository. Many of the images are accompanied by interpretations and links to publications.

The VSA format allows viewing and downloading the high-resolution images, to be used in research and teaching (providing that the IP is acknowledged). Anyone can also register as an author and submit their own images, or interpretations of the existing images. For more information, please contact T. Torvela or R. Butler.

VSA **The Virtual Seismic Atlas**
www.seismicatlas.org
"sharing the geological interpretation of seismic data"

Using High Resolution Digital Elevation Model of the Krafla Fissure System, NE Iceland, to Examine Geologic Rates of Deformation

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Krafla volcano is situated on the divergent plate boundary in the Northern Volcanic Zone of Iceland in a 5-10 km wide and 100 km long fissure swarm. Fissure eruptions characterise the volcanic activity in Krafla, highlighted by a rifting episode in 1975-1984 which activated an 80 km long segment of the Krafla fissure swarm.

One of the highest resolution Digital Elevation Models (DEMs) available is the METI and NASA's ASTER Global DEM, which gives a maximum 30 m resolution in the near-infrared. However, the purpose of this research is to better understand the roles that magmatism and tectonics have in accommodating strain across the whole of this region, and to do this a much higher resolution dataset is needed.

High resolution LiDAR surveys were acquired over the Krafla fissure swarm in August 2007 and September 2008. Thse data have been interpolated using the natural neighbour algorithm to create a 1,300 km^2 high resolution (~0.5 m) Digital Elevation Model (DEM) of the area.

The eruptive history suggests that the Krafla fissure swarm may not have been active for the whole of the last 10 ka, and that other rift segments may accommodate extension at some periods. Using the DEM and ages of known lavas, we have estimated the average rate of extension on during the post-glacial period (10 ka), and attempted to determine whether faulting has been proceeding at a steady rate during this time period. Furthermore, we will present a comparison of the long-term rates with the present-day deformation measured using InSAR and GPS at Krafla to determine whether the present-day deformation can be used as a reliable indicator of long-term rates of activity.

The Tectono-geomorphic features of Apennine Fault Scarps Mapped Using Combined Ground Penetrating Radar and Terrestrial Laser Scanning

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Greater knowledge of the geomorphological setting of faults and consequently, more accurate paleoseismological interpretations can provide the framework for more reliable assessments of the long term seismic hazards posed by normal faults in the Apennines. Using combined ground penetrating radar (GPR) and terrestrial laser scanning (TLS) datasets we present a study of the tectono-geomorphic expression of bedrock fault scarps in the central Apennines. Previous investigations have highlighted the challenges in the interpretation of these structures resulting from differentiating between those scarps formed by recent tectonic exhumation and those by geomorphological exhumation. This problem may only be overcome by detailed investigation of the tectono-geomorphological setting of each fault. Our work on three Apennine fault scarps illustrates that the surface expression of the scarps result from the interaction between footwall incision, hanging wall sedimentation, channel incision and landsliding as well as fault slip rates and fault linkage. Increased understanding of these mechanisms will aid our understanding of the complicated relationship between bedrock faulting and geomorphic processes, contributing to improved understanding of seismic hazards in the central Apennines.

Kick & Cook Experiments on Natural Peridotite: Simulating Episodic Creep Below the Seismogenic Zone During the Seismic Cycle

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The microfabric development in peridotite is analyzed in deformation and annealing experiments, which are designed to simulate the natural stress history in the upper mantle of the oceanic lithosphere just below the seismogenic zone during the seismic cycle. The samples are deformed in a servohydraulically-controlled solid medium deformation apparatus at 600°C, a constant strain rate of $10^{-4}s^{-1}$ and confining pressure of 1.0 GPa and 2.0 GPa ("kick" experiment). In some experiments deformation is followed by annealing for 15 h to 70 h at zero nominal differential stress, temperatures of 700°C to 1000°C and 2.0 GPa confining pressure ("kick & cook" experiment). We use coarse-grained peridotite from the Almklovdalen peridotite complex as starting material. The "kick" experiments yield maximum differential stresses of ca. 1.2 GPa to 1.6 GPa. The resulting microfabrics are analyzed by optical and electron microscopic techniques. The microfabric indicates brittle and crystal-plastic deformation of olivine. Intragranular microfaults, which can be crystallographically controlled, and deformation lamellae parallel to (100) occur in deformed olivine crystals. In TEM, the optical visible deformation lamellae are represented by a high density of straight dislocations aligned parallel to [001], indicating that they are [001] screw dislocations. Cataclastically deformed olivine is characterized in TEM by domains with a high dislocation density, which are bound by poorly-ordered dislocation walls. After annealing at 1000°C, the microfabric is characterized by very fine-grained recrystallized olivine grains arranged along microfaults and surrounding olivine porphyroclasts. In TEM, the new olivine grains contain well-ordered low angle grain boundaries and a high dislocation density. These observations indicate subgrain rotation as predominant recrystallization process. New defect-poor grains and a large scatter of new orientations imply also growth of defect-free crystallites during annealing, which were initially generated during the "kick" experiment. The olivine microfabrics from our experiments compare well with microfabrics observed from naturally deformed peridotites of the Baldissero complex in the Western Alps. Similar olivine aggregates in naturally deformed peridotites are frequently interpreted as indicative of deformation by dislocation creep and recrystallized grain size is used as paleopiezometer assuming steady-state conditions. The microfabrics of our experiments, however, suggest a development through an initial stage of high stress brittle and localized crystal-plastic deformation followed by recrystallization at low stress.

Geodynamic implications for the Cyclades - the low-angle normal fault system on Kea

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We present new data on the overall structure of the island of Kea, in the W. Cyclades. This has been re-mapped and investigated within the international interdisciplinary project ACCEL (Aegean Core Complexes along an Extended Lithosphere) for its implications for the postulated West Cycladic Detachment System.

Situated in the Aegean extensional regime, Kea hosts a crustal-scale shear-zone that moved through the brittle/ductile transition zone, with textural evidence for several progressive deformation stages. During its formation, the low-angle normal fault system interacted with high-angle brittle normal faults. In contrast to the N- and E Cycladic Detachment Systems, which are dominated by a NNE-directed shear-sense, data from Kea indicate the formation of an extensional structural domain with a S- to SSW-directed shear-sense.

In the W. Cyclades (Kea, Kythnos, Serifos, Sifnos), LANFs are represented by up to 10´s of metre-thick fault-rock horizons that were active from ductile to brittle conditions, with consistent top-SSW-kinematics. Stretching lineations in both ductile and brittle/ductile rocks show a counterclockwise rotation of the overall stress-field, from E-W to N-S, consistent with data from other parts of the Cyclades.

Thermochronology reveals Miocene Ar/Ar white-mica ages, documenting the exhumation history and development of the LANF system during ongoing greenschist-facies metamorphic conditions. Footwall rocks show a decrease in peak cooling-age near major shear zones, due to ongoing deformation (recrystallization) during exhumation.

The footwall was pervasively affected by top-SSW shear, with S-C-C´ fabrics found throughout the ca. 450 m exposed structural thickness. However, some strain partitioning occurred towards the LANF, with higher strain-rates. Supporting detailed investigations into fault-rock evolution are to be made, to constrain the deformation mechanisms during LANF formation.

The results, in combination with PT-path calculations, link the lithostratigraphy of Kea to the Attic-Cycladic Intermediate and Upper Units of the adjacent Attica/Lavrion area, increasing the dimensions of the West Cycladic Detachment System and thus its likely displacement.

Sliding Behavior of Calcite and Dolomite Marbles at Seismic Deformation Conditions

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Our understanding of earthquake physics is hampered by the poor knowledge of the evolution of the friction coefficient (μ) in at deformation conditions typical of the seismic source. Insights can be gained by experiments using a novel rotary shear deformation apparatus, SHIVA (Slow to HIgh Velocity Apparatus) which, by exploiting the large available power (300 kW), is capable of extending the performance of previous experimental apparatus to more realistic (i.e., approaching natural) conditions. Here we present results from experiments performed on samples of Carrara (98% calcite) and dolomite (98% dolomite) marbles. The two rocks were selected because many earthquakes worldwide nucleate within and rupture through carbonates sequences (e.g., L'Aquila 2009 M_w 6.3). Tests were conducted on hollow cylinders (50/30 mm ext/int diameter) at velocities of 0.001-6.5 m/s and normal stresses up to 40 MPa. Each experiment consists of three steps: (1) loading of the sample to the target normal stress; (2) acceleration to the imposed slip rate; (3) deceleration until the target slip or duration is reached. The two marbles show a similar evolution of friction: μ rapidly increases to reach an initial peak value (~ 0.6) followed by a dramatic reduction towards an extremely low steady-state value (< 0.1), comparable to previous experiments performed at lower normal stresses (< 13 MPa). Steady-state friction of calcite is slightly lower than that of dolomite. The dramatic reduction in friction occurs over a slip weakening distance in the range 0.4-2.5 m for calcite and 0.1-0.4 m for dolomite. In calcite, the decrease in friction follows an exponential decay, whereas in dolomite the friction drop is complicated by a short-duration phase of re-strengthening. Preliminary investigations on calcite marble indicate that axial shortening measured during the experiments is inversely correlated to slip rate. At low slip rates (<0.2 m/s), samples shorten significantly due to bulk fracturing and loss of gouge material from the sliding surface. However, at high slip rates (>0.5 m/s) shortening is negligible and loss of gouge material is generally not observed. Microstructural analyses suggest that negligible shortening may be related to the formation of `protective' layers of CaO (lime) along the slip surface during fast slip, resulting in low wear rates and extremely thin (compared to silicate-bearing rocks deformed under similar conditions) slipping zones. The observation of decomposition layers in the post-experimental slipping zone seems to support this, although more elaborate analyses are currently in progress.

Postseismic Deformation of the 2009 L'Aquila Earthquake (M6.3) Surface Rupture Measured Using Repeat Terrestrial Laser Scanning

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We have conducted an innovative repeat terrestrial laser scan survey at four sites on the NW-SE striking surface rupture of the 2009 L'Aquila earthquake (M6.3). Between 8 – 126 days after the earthquake we repeatedly laser scanned the surface of four road sections cross-cut and vertically offset by the surface rupture. We registered the laser scan data from each site into a footwall static reference frame and interpolated the data to form representative road surfaces. We were able to model rupture afterslip and associated near-field postseismic deformation at each site in the immediate hangingwall with millimetre to sub-centimetre precision. We identify that the magnitude of postseismic deformation observed at site PAG towards the centre of the rupture persists sites SP and EP towards the SW tip of the rupture. The postseismic deformation observed at site TM, towards the NW tip of the rupture however, shows a decrease in postseismic deformation from that seen at PAG. We correlate the large magnitudes of postseismic deformation at sites on the SW end of the rupture to an increased coseismic slip deficit in this part of the fault zone, thought to be the driving mechanism of afterslip and near-field postseismic deformation. Conversely, the lack of significant postseismic deformation observed along the NW section of the rupture at site TM is thought to be controlled by the lack of a significant coseismic slip deficit within this part of the fault zone.

Dry and Wet Frictional Strength of Clays at Low to Medium Normal Stress

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Weakness of some faults is being linked to the presence of phyllosilicates, which are known to have very low coefficients of friction. Their weakness has been explained by their sheet-like structure facilitating sliding along the basal plane between mineral layers. So far, test have mostly concentrated on uniform normal stresses and the normal stress-dependent frictional behaviour of clays remains unclear.

We measured frictional strength of 10 different phyllosilicate powders with a controlled particle size (<45 um) at a range of effective normal stresses (5MPa - 100MPa) using a triaxial deformation apparatus. Tests were performed both on dry and water-saturated powders (10 MPa pore pressure). Clays included: talc, pyrophyllite, montmorillonite, illite, muscovite, biotite, phlogopite, kaolinite, lizardite and chlorite.

Our results confirm that phyllosilicate powders are weak with friction coefficients ranging from 0.22 - 0.44 (dry) and 0.12 - 0.38 wet. Shear stress increases linearly with normal stress and friction coefficients are mostly constant between 5MPa and 100 MPa effective normal stress. Dry frictional strength of talc, pyrophyllite, phlogopite, muscovite and chlorite is correlated with calculated interlayer bond strength energy between minerals layers, but this is not true for kaolinite and lizardite in our study. All samples weaken under wet conditions, especially montmorillonite and chlorite, and the order of frictional strength is not the same for wet and dry powders. If octahedral structure is taken into account, then minerals with a dioctahedral layer show higher friction coefficients than equivalent structured trioctahedral minerals.

In addition to confirming the influence of crystallographic structure on phyllosilicate strength, we conclude from our tests that friction coefficients measured at higher normal stresses are applicable to lower stresses as well as the influence of normal stress seems low.

Quantifying and Comparing the Evolution of Dynamic and Static Elastic Properties as Crystalline Rock Approaches Failure

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Elastic properties are essential parameters whenever stresses are measured in the crust. Dilational microcracks within rocks strongly influence these properties. The static and dynamic elastic properties were measured for crystalline rock as it approaches failure. In this study, increasing-amplitude cyclic loading experiments were carried out to investigate and quantify the effect of microcracking on the elastic properties, and to establish a relationship between static and dynamic measurements. Increasing-amplitude stress cycling causes an increase in the density of microcracks damage which results in a decrease in Young's (~2.6% static and ~2.3% dynamic), and an increase in Poisson's ratio (~8% static and ~2% dynamic) at a constant stress level (70MPa in this example). Static and dynamic elastic properties also show stress-dependency during loading. If a single cycle is considered (cycle 3 in this example), the static and dynamic Young's modulus increases from ~52GPa to 66GPa and increases from ~53GPa to 66GPa respectively; the static Poisson's ratio increases steadily from ~0.2 to 0.26 and the dynamic Poisson's ratio increases from ~0.24 to 0.26 within the first 20MPa and then increases nominally to ~0.27.

The dynamic Young's modulus is greater throughout the experiment than the static Young's modulus. There is an increase in the difference between static and dynamic Poisson's ratio from 3MPa to 20MPa differential stress after which it rapidly decrease towards equality. During the latter cycles, the static and dynamic Poisson's ratio are equal at 90MPa differential stress and beyond this differential stress level, the static Poisson's ratio is greater than the dynamic Poisson's ratio.

The measurement of the static Young's modulus is in agreement with the dynamic Young's modulus. There is a significant discrepancy between the static and dynamic Poisson's ratio. Bulging of the sample during the experiment is affecting the static Poisson's ratio but cannot completely describe the difference seen between static and dynamic properties. A linear relationship with very high correlation between the static and dynamic Young's modulus was established. The gradient and intercept of the linear relationship change as the number of cycle increases.

Influence of Hydrothermally Produced Talc Upon Fault Strength

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The effect of low-temperature metamorphic and metasomatic reactions and frictionally weak reaction products upon fault behaviour is becoming increasingly evident. We performed experiments to establish the kinetics of the hydrothermal reaction lizardite + quartz ⇒ talc + H_2O. This reaction may be significant at oceanic spreading centres where the production of weak phyllosilicates, such as talc, by hydrothermal reaction may have considerable effect upon lithospheric strength. The production of mechanically weak reaction products is currently favoured as a potential facilitator of aseismic creep, as observed on major fault zones including the San Andreas Fault. Additionally, the syntectonic growth of reaction products may influence resistance to sliding.

To determine experimentally the effect of talc growth upon fault behaviour, we conduct three types of deformation experiment. In preliminary tests, a talc gouge was introduced to sawcut samples, juxtaposing serpentinite and quartzite on opposite sides of the fault surface. These samples were subjected to deformation at constant displacement rate at elevated confining pressure, temperature and pore pressure. Further experiments take the form of “cook and kick” or “cook and creep” tests. So-called “cook and kick” tests involve the growth of a talc veneer by reaction of the serpentine and quartzite surfaces at their interface over 72 hours, before carrying out constant displacement rate deformation. Novel “cook and creep” experiments involve application of a constant load during talc growth. These tests examine not only the effect of the presence of talc upon fault strength but also how the progress of the reaction itself may influence apparent shear strength. Microstructural study to elucidate deformation mechanisms is in progress.

Comparison of the Brittle Deformation Characteristics of Darley Dale and Pennant Sandstones

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Tests have been performed on Darley Dale and Pennant sandstones as part of an ongoing project exploring the formation and sliding of faults under varied stress conditions. Tests have been performed using a triaxial machine, in both extension and compression. The tests were on both intact and pre-cut samples, with the saw-cuts at 35°, 45° and 55° to the length of the sample. For the saw-cut tests, both constant confining pressure and constant normal stress conditions were implemented.

Results can be displayed as Mohr diagram plots and octahedral stress plots. Results have also shown that the friction angle is different between compression and extension in Darley Dale sandstone, and that the fracture angle in extension is also very low (approximately 16°). Darley Dale sandstone is considerably weaker than Pennant sandstone. The two rock types also form different fracture angles in intact samples. Darley Dale sandstone fractures at approximately 36° in compression, whereas Pennant sandstone fractures at approximately 31° under the same conditions. These differences are important for this project, as results have shown that Darley Dale sandstone is not strong enough for the project, as a material is required that will slide along saw-cuts rather than forming fresh fractures. Darley Dale sandstone has formed fresh fractures when tested using angles of 55° and 45°, so a stronger material, such as Pennant sandstone was required.

Ongoing work uses Pennant sandstone, because a wider range of pre-cut fault angles can be used without precipitating the formation of fresh faults. Tests will focus on the effects of variations in pore fluid pressure and the presence or absence of fault gouge of different types. The tests involving fault gouge will consist of anisotropic and isotropic materials, so that stress refraction effects can also be investigated. Analysis of structures will be performed on a macroscopic and microscopic scale, so the influence of micro-cracks or meso-cracks forming as a result of raising pore pressure sufficiently to induce hydraulic cracking can be studied.

Lithological Controls on 3D Fold Geometry in Mechanically Layered Rocks

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Folding and thrusting are key processes in accommodating shortening in evolving orogens. In the outer parts of mountain belts, the combination of tectonism and sedimentation often leads to viable petroleum systems where folds trap migrating hydrocarbons. A key aspect of the success of these traps is the 3D fold geometry, which must prevent up-plunge hydrocarbon escape. Fold shapes in a multilayered system are governed by the fold mechanism, and the rheology of the layers. In sedimentary environments where laterally heterogeneous thicknesses of interbedded carbonates, clastics, and evaporates may be present, predicting the sub-surface geometry of structures is challenging.

We present field data combined with satellite and seismic interpretation from the Zagros fold and thrust belt of SE Turkey where Neogene shortening has affected an Ordovician to Miocene aged sedimentary pile comprising shales, sandstones and carbonates. Carbonates capping the sequence allow 3D fold geometries to be ascertained at surface with a high degree of confidence, whilst the underlying ~1km of shales and mudstones allows folds to develop that depart substantially from standard “text-book” geometries. Beneath these incompetent units a further 1.7km of carbonates and clastics overlie Ordovician shales up to 1.5km thick. In relatively low strain sections asymmetric, angular, kink-like folds form long wavelength structures and thrust faults rarely reach the surface. With increasing strain, the wavelength/amplitude ratio decreases and thrusts cut through the fold limbs.

Folds are interpreted to detach above a thick sequence of Ordovician shales. They originate by buckling of the competent units with initial perturbations provided by sedimentary heterogeneities. As the folds amplify, thrusts form in the competent units above the shale and propagate upwards with fold amplification dominated by fault-tip ‘tri-shear’. In this model, thrust formation is governed by the location of the initial buckle folding. Since the thrusts mostly originate from the top of the Ordovician shales, they form a linked system so that displacement can transfer from one structure to the next along strike of the orogen. It is the interaction of folds with varying amplitude which is essential in the identification of viable hydrocarbon traps. Incorporation of numerical models which allow ductile folding and brittle failure with these field and remote sensing based studies will inform further exploration in similar areas and allow investigation of the effects of parameters such as lithological thickness on the location and geometry of structures in collisional orogens.

Geometry of Active and Passive Sheath Folds

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Passive sheath folds develop by the geometric amplification of initial irregularities and folds as originally suggested by Cobbold & Quinquis. Where layering becomes rheologically significant resulting in discontinuities, then *active sheath folds* may form in which the inner nose of the sheath undergoes a translation relative to the surrounding envelope and may "intrude" into adjacent layers. Consistent patterns of shear sense within sheath folds reflect *passive sheath folding,* whilst marked deformation gradients and detachments around the eye-shaped sections are consistent with *active sheath folding* where the sense of relative shear reverses across the axial surface. This case study forms the first systematic 3-D analysis of an individual sheath fold whereby identifiable marker layers are traced across a total of 34 y-z serial section planes normal to the length (x) of the sheath fold. This allows 455 ellipses to be measured from this single fold, and results in a complete geometric analysis of an active sheath fold. Weak layers which form detachments may define different shaped sheath folds relative to the other layers, with the sense of cut-off along detachments reversing across the axial surface of the sheaths. The inner tongues of sheath folds may display bifurcating en-echelon hinges that are oblique with respect to the outer sheaths. Folded lineation (Ln) patterns around sheath closures display asymmetric “star-burst” patterns indicating recrystallisation of Ln as the sheath hinge rotates. Asymmetry of Ln patterns across the axial surface reflects greater rotation and recrystallisation of Ln on the upper limb of the fold. Marker layers which act as detachments within sheath folds typically have lower hinge/Ln angles and lower limb/axial surface angles for any given distance along their x-axis when compared to non detachments i.e. detachment layers are more intensely folded. Active sheath folds are therefore non-similar in this respect. We have, for the first time, combined traditional t’ analysis of fold limbs with t’ data for curvilinear hinge lines. Isogons drawn around x-z and y-z limb profiles together with x-y hinge profiles all display overall convergent patterns, although the classical limb profiles and the new hinge profiles reveal differing fold classes. The elliptical y-z ratios obtained from individual marker horizons are very similar to the values obtained from all layers exposed in the single slice where that marker first appears. Thus, the y-z cross sectional shapes exposed in any 2-D y-z slice may be confidently used to predict the geometry of any particular marker horizon back along the x-axis in the third dimension. This self-similarity may be of value when tracing stratiform mineralised horizons in large-scale sheath folds.

Digital Field Mapping for Structural Geologists

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Best practice in field collection of data has scarcely changed in over 100 years. Other industries ranging from topographic mapping through to utilities companies updating map based data have progressively adopted digital mapping systems with an appropriate GIS “back office” system. In geology this transition has largely not happened, in part due to innate conservatism, and the perception that suitable field hardened tablet pc’s are too expensive, but largely due to the lack of an appropriate digital interface that allows the user to collect geological information in a manner that replicates and augments the traditional paper based approach.

In this poster we show and demonstrate the work undertaken by Midland Valley and its Academic Partners to develop a digital mapping system for geologists. The interface for data collection and field mapping is specifically designed for geologists rather than clumsily adapted from another sector. The system, FieldMove, has been designed for simplicity for the generalist and specialist alike and links directly to established GIS applications. In addition, full heritage data can be included ranging from scanned maps through to industry standard interpretation and modeling systems.

Customizable stratigraphic and symbol sets with lithological tables can either be set up in advance or “created on the fly”. A fully featured digital notebook, GPS “co-cursor” and geo-referenced field photographs are amongst the tools provided. The user can opt to map on a traditional 2d map projection or to automatically project this onto a DEM and access the 3d visualization interactively in the field with MoveViewer.

The application can be used standalone or in conjunction with Midland Valley’s model building and analysis software, Move, to enable structural analysis, section and 3d modeling and forward modeling to be carried out upstream in the mapping program to enhance interpretational and focus data collection.

Our trials have demonstrated that this process is faster than conventional field slip / fair copy systems and frees up time from fair copy transcription which in turn radically reduces error. The digital system has been trialed in a range of environments from the Alps and Australian Outback to rainy Scotland. FieldMove software is available free to academics for teaching and research.

Strains related to normal faulting: mapping, analysis and elastic modeling

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Fault interactions involve the partitioning of displacement between mechanically coupled fault surfaces and the three-dimensional strain of the intervening volume. We discuss an example from seismic reflection data from the Inner Moray Firth where, in a series of left-stepping en-echelon normal faults, the total vertical offset of a geological interface is partitioned between observed, discrete, fault offset and apparently continuous deformation (at least at the scale of observation). The latter continuous deformation is manifested as rotation of the geological interface and is recorded by measuring apparent dip along a series of parallel transects. Maps of the apparent dip variation serve as semi-quantitative estimates of strain in the vicinity of the faults. We use this pattern of faulting and discrete offsets to drive an elastic dislocation forward-model and examine the distribution of elastic displacements and strains in the volume. Despite the obvious mechanical contrast between a homogeneous elastic continuum and a syn-rift sand shale sequence, there is a strong correspondence between the observation-based strains and the strains predicted by the elastic model. This correspondence is particularly pronounced in the units above the fault tips where our elastic displacements recreate the seismically-imaged monoclines.

Can we use Lines of no Finite Elongation to Predict the Orientations of Cataclastic Deformation Bands?

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Cataclastic deformation bands typically form in high porosity sandstones adjacent to and ahead of through-going fault surfaces. As such, the orientations of cataclastic deformation bands may provide information about the geometry and magnitude of finite strains within the wall rocks surrounding larger faults. This information may in turn provide clues as to the geometry and magnitude of the elastic strain field at the time of faulting and, as proposed here, the volume changes at the time of faulting.
Similarities between the results of trishear numerical models and claybox experiments of fault propagation folding led previous authors to propose that secondary fractures may develop parallel to lines of no finite elongation (LNFEs). We test this proposal by comparing the orientations of deformation bands preserved in the footwall of a seismically active thrust, exposed at Clam Beach, McKinleyville, CA with the orientations of LNFEs predicted by a suite of two-dimensional (plane strain) trishear models. Although simplistic, the assumption of plane strain deformation provides a reasonable starting point in the absence of firm constraints on three-dimensional fault geometries and displacement gradients. Models incorporating trishear angles of 50 and 70°, and the maximum potential thrust offset of 56m, predict negligible strains in the footwall of the McKinleyville thrust along the Clam Beach section. Models incorporating a trishear angle of 90° predict that deformation occurs within the footwall up to ~120m away from the trace of the thrust, with maximum strains (Rxz) of 1.2. By contrast, the orientations of cataclastic deformation bands imply bulk strains (Rxz) of 3 to 5 within the footwall, assuming that deformation bands form parallel to LNFEs. This prediction contrasts with a previous study, which used Fry analysis of sand grains within and adjacent to the cataclastic deformation bands to calculate footwall strains of 1.2 to 1.7. It is therefore unlikely that the deformation bands seen at McKinleyville have formed parallel to LNFEs, at least those modelled assuming constant volume plane strain deformation. It is, however, possible that the deformation bands may have formed parallel to LNFEs if there was dilation in addition to slip along individual deformation bands. This suggestion is consistent with some experimental data that show dilation during slip localization within poorly or non-consolidated materials.

Crustal Stacking and Expulsion Tectonics During Continental Subduction: P-T-Deformation Constraints from Oman.

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The northeastern continental margin of Oman in the Saih Hatat region is characterised by high-pressure (HP) chloritoid- or carpholite-bearing metasediments and highly deformed mafic eclogites and blueschists in a series of tectonic units bounded by high-strain ductile shear zones. New data on the upper cover units of this HP nappe stack indicate that all of them underwent similar P conditions to the underlying Hulw structural unit (with a cooler exhumation P-T path). Early SSW-directed crustal thickening during ophiolite emplacement created recumbent folds and strong schistose fabrics in these Permian–Mesozoic shelf carbonates and was followed by later NNE-dipping normal sense shear zones and normal faults. The Mayh unit shows high strain in a 15-25 km long sheath fold that likely formed at carpholite grade pressures of 8-10 kbar. We show that there are no significant P differences across the Hulw shear zone (‘upper plate – lower plate discontinuity’) nor between the overlying Mayh, Yenkit-Yiti and Ruwi units. Post-peak metamorphic exhumation of the HP rocks was therefore accomplished by bottom-to-SSW (rather than top-to-NNE) active footwall extrusion beneath a fixed, static, passive hanging-wall. Footwall uplift beneath these passive roof faults resulted in progressive expulsion of the HP rocks from depths of ~80-90 km (eclogites) and mainly 30-35 km (blueschists and chloritoid/carpholite-bearing units) during the Campanian – Early Maastrichtian. Oman thus provides a detailed record of how continental material (thick platform shelf carbonates) progressively jammed a subduction zone and emphasizes the contrasting behaviour between cover units and their underlying basement.

North-West Verging nappes in a major Tethyan Sedimentary Allochthon in the Eastern Himalaya

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Recent structural mapping in north central Bhutan has revealed north-west verging macroscopic fold nappes in Tethyan carbonate and clastic sediments which structurally overlie migmatitic gneiss and leucogranite of the Greater Himalayan Sequence. This area is the northern part of a much larger (~80km x 10-50km) allochthon of Tethyan rocks that lie everywhere structurally above the Greater Himalayan Sequence of high grade metamorphic rocks. The recumbent folds within this allochthon verge in the opposite direction to the generally southward-verging orogen and may have been produced as a result of top-to-the-north motion along the underlying South Tibetan detachment. Similarly-verging structures have been reported from central Nepal where their formation has been shown to be compatible with both wedge extrusion and channel flow models for the exhumation of the underlying mid-crustal gneisses. The results of this study provide constraints on direction of continental collision and tectonic models for the evolution of the eastern Himalaya including upper and middle crustal coupling and brittle and ductile deformation.

The Cantabrian Thrust Belt: Pyrenean Folding of Variscan Thrusts – Refolding and Reorientation??

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The Cantabrian Mountains, north-western Spain, comprise a Hercynian, arcuate, thin-skinned foreland thrust-and-fold belt constituting the Ibero-Armorican Arc (IAA), forming a continuous 800 km range along the Iberian subplate northern boundary. The Cantabrian and West-Asturian-Leonese Zones of the Iberian Massif preserve Variscan basement of Precambrian and Palaeozoic age, which have subsequently undergone Pyrenean deformation. This is reflected by basement uplift, internal deformation, reactivation of previously folded Variscan thrusts, and horizontal shortening (60%+ estimates) viewed within northward-vergent structures of the Somiedo-Correcillas thrust unit (SCZ).

Lateral changes in thrust fault geometry occur in all fold-and-thrust belts across so called transverse zones, thought to be related to pre-existing basement faults, lithological changes and multiple thrust development in duplex / antiformal stack structures. Causative structures are often concealed and not fully studied. As a result, three-dimensional topology, geometry and kinematics of selected thrust systems have been studied to fully analyse their evolution and cause / effects of lateral changes in thrust belts within the well-understood and comprehensively mapped SCZ within the southern Cantabrian Arc.

Findings delineated from newly-developed thrust nomenclature map analysis indicate distinct structural style changes from IAA southern to northern zones. Thrusts dominate within southern zones, where overturned / non-overturned thrust sheets and thrusts are observed, which change to fold dominated regions within north-western limits. Lateral variations are further denoted through stratigraphic separation diagrams which illustrate differing structural styles, lateral ramps / transfer structures as well as lithological pinch outs.

Transport parallel cross-sections are used to determine thrust kinematic evolutions using key movement indicators to give further insight into degrees of shortening, reorientation, lateral variations and overall thrust sheet evolution within a regional context. These findings suggest a complex tectonic evolution involving Variscan and Pyrenean (Alpine) effects giving rise to deformation and reorientation of the original movement template.

Thrust Fault Evolution and Hydrocarbon Sealing Behavior, Qaidam Basin, China

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Fault seal analysis has in the past been focused on extensional systems. However, fault behaviour in terms of fault sealing is also critical within compressional thrust systems. The results of an evaluation of thrust fault evolution and hydrocarbon sealing behaviour in the compressional Qaidam basin of western China are reported.

Large scale seismic analysis, restoration and 3D modeling are used to evaluate the evolution of faults within this thrust system and as a platform for detailed seal analysis. The results allow assessment of the timing of deformation, shortening, shortening strain, and strain rate.

Detailed structural maps of exceptionally well exposed outcrops are used to extract information on fault geometry and micro-structural analysis (e.g. SEM) and petrophysical measurements are used for assessment of the deformation mechanisms associated with sealing properties. Future analysis of drilling cores will extend this work to sub-surface prediction.

The work illustrates the value of a macro to micro approach on thrust fault evolution and hydrocarbon sealing behavior, and aims to identify the critical parameters that contribute to improving fault seal analysis in thrust systems.

Morphotectonic Analysis of Thrust-Faulted Zone Using DTA. A Case Study for the Villany Hills, Hungary.

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In the framework of our earlier study the brittle tectonics of the Villany Hills and its surroundings was examined. Based on the measured striae and other kinematic indicators, different structural phases were determined from Cretaceous to date. It was an important task to determine how to relate the development of the different morphological elements to the tectonic features. The investigation is based on a DEM-50. After the careful delineation of the study area, some hypsometric and shaded relief models were created. Based on the latter model, lineament maps were also derived which were compared to the known tectonic lines. A number of numerical derivation methods were compared to slope and aspect maps calculations in order to assess maps were used to identify areas of steep hill slopes, uniform aspect and linear morphological boundaries potentially indicative of tectonic influence. The created profile curvature map was thus used to detect the abrupt slope breaks and also to observe the convexity or concavity of the valleys. More than 200 digital morphologic cross sections were made inside the study area, which show the different elevation distribution in the direction parallel and transverse to the morphological features such as major valleys and to known tectonic lines. Valley and ridge lines were identified as drainage and watershed lines by means of digital drainage network analysis. A morphological lineament map containing linear valleys, ridges and slope breaks was derived form the drainage model and profile curvature map, respectively. The spatial distribution of lineaments was characterized by a lineament density map. Based on the morphometrical analyses together with geological considerations, four morphological sub-areas were delineated. These sub-areas were subsequently further investigated in more detail using the above described methods. Results show that the orientations of the measured structural data correlate to the orientations of the various observed morphological lineaments such as drainage elements. It is interesting that the identified lineaments do not coincide with the geological boundaries. The tectonic lines and the morphological lineaments do coincide especially along the Pecs-water valley and on the southern hillside of the Villany-Hills. Based on the curvature maps and the classified slope maps, different morphological surfaces were determined, which are bordered by significant slope breaks. The valley and ridge networks are skeleton-like features in the Villany Hills, while they are parallel in the Baranya Hills following the main NW-SE tectonical lines. Based on the study, the morphological elements in the study area are mainly directly or indirectly related to the tectonic genetics of the area.