Tectonic Studies Group Annual Meeting 2012
Technical Programme – Final

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Day 1 – Wednesday 4th January
10.00 Registration and set-up
11.00 **Welcome**

Session 1: Deformation Processes – General
Chair: Ian Alsop
11.15 – 12.45

Proglacial to subglacial deformation and permafrost-glacier interactions associated with a Pleistocene ice sheet margin.
Phillips, E., Waller, R., Lee, J. & Murton, J.

Branching shear zones – examples from Saudi Arabia.
Meyer, S. & Passchier, C.

Stress directions and magnitudes derived from stylolites.
Koehn D., Toussaint, R., Ebner, M., Bons, P. & Kulzer, F.

Structural control of the copper-cobalt grade distribution at the Konkola ore deposit, Zambia.
Torremans K., Muchez Ph., Sintubin M. & Sikazwe O.

How to form folds with convergent cleavage fans in pelites.
Debacker, T.N., Mathijs Dumon, M., Verniers, J. & Sintubin, M.

Stress inversion and tensor separation using OFA-clustering – a test on artificial and real data.
Hansen, J–A., Bergh, S. G., Osmundsen, P. T. & Redfield, T.

Posters and lunch
12.45 – 13.30

Session 2: General Structural Geology
Chair: Maarten Krabbendam
13.30 – 15.15

Deformation structures associated with the emplacement of high-level intrusions, Henry Mountains, Utah.
Wilson, P., McCaffrey, K., Davidson, J., Murphy, P. & Jarvis, I.

Cambrian successions and detrital zircon geochronology of Megumia: southern Nova Scotia and North Wales as dispersed fragments of a peri-Gondwanan basin.
Pothier, H., Waldron, J.W.F., Schofield, D.I., Barr, S.M. & White, C.E.

A late-Ordovician 'Tornquist' supra-subduction shear zone system on the NE margin of Eastern Avalonia: the Caledonides of N & E England.
Thomas, C.W., Woodcock, N.H. & Schofield, D.I.

Monian (Penobscottian) thrust tectonics on the outboard margin of East Avalonia.
Schofield, D.I., Leslie, A.G., Burt, C.E., Morgan, D., Wilby, P.R. & Leslie, A.B.

A Caribbean-style plate in the Iapetus Ocean?
Waldron, J.W.F., Murphy, B. & Schofield, D.I.

Reconstruction of the kinematic evolution of the North-Armorican shear zone, Brittany, France.
Derez, T., Vandycke, S., Haerinck, T., Berwouts, I. & Sintubin, M.

Cross-strike discontinuities: The development of the Loch Maree Transverse Zone.
Kelly, M.J., Leslie, A.G., Clarke, S.M. & Williams, G.D.

Posters and refreshments
15.15 – 15.45

Session 3: Structural Geology: Himalayas and Tibet.
Chair: Richard Phillips
15.45 – 17.00

Thrust fault evolution and hydrocarbon sealing behaviour, Qaidam Basin, China.
Pei, Y., Lickorish, H., Li, A., Bradbury, W., Paton, D. & Knipe, R.J.

Micro-geodynamics of the Karakoram fault zone, Ladakh, NW Himalaya.
Wallis, D., Phillips, R. & Lloyd, G.

The timing and structural style of the India-Asia collision from plate kinematic and seismic observations in the equatorial Indian Ocean.
Bull, J.M., DeMets, C., Krishna, K.S., Sanderson, D.J. & Merkouriev, S.

Using isotope geochemistry to unravel the mysteries of the Main Central Thrust, Sikkim Himalaya.
Mottram, C.M. , Harris, N.B.W., Parrish, R.R., Argles, T.W. & Warren, C.J.

Tectonics of the eastern Himalaya: U(-Th)-Pb geochronology of structures in Bhutan.
Greenwood, L.V., Parrish, R.R., Argles, T., Warren, C. & Harris, N.

Poster session, with refreshments
17.00 – 18.30

Day 2 – Thursday 5th January

Session 4: **Carbonate Fault Zones I**
Chair: Zoe Shipton
09.15 – 10.15

Anisotropy of fracture density and connectivity along and across a fault zone and its effects on fluid transmissibility – case study from the Gubbio Fault.
Sagi, D., De Paola, N., McCaffrey, K.J.W. & Holdsworth, R.E.

Carbonate-hosted normal faults in Malta: Variations in deformation in distinct lithofacies.
Michie, E.A.H., Healy, D., Haines, T.J., Alsop, G.I., Neilson, J., Timms, N.E. & Wilson, M.E.J.

Core and shale smear characterization along extensional faults in late pre-rift carbonates (Suez Rift, Egypt): Implications for fluid flow.
Elvik, L., Bastesen, E., Rotevatn, A., & Hatleseth, S.M.S.

The effect of fault core composition and geometry on the permeability structure of faults in carbonate reservoirs.
Bastesen, E. & Rotevatn, A.

Poster session, with coffee and refreshments
10.15 – 11.00

KEYNOTE LECTURE
11.00 – 11.30
Scaling of brittle failure in space and time: impact on the predictability of volcanoes and earthquakes.
Ian Main

Session 5: **Fault Zones and Processes I**
Chair: Richard Walker
11.30 – 12.15

Spatial characterization of deformation in high porosity sandstones: from outcrop data to fluid flow circulation.
Saillet, E., Shipton, Z. & Lunn, R.
Characterising fracture porosity around fault zones.
Farrell, N.J.C., Healy, D., Bond, C.E. & Alsop, G.I.

The formation of breached relay zone geometries from splay propagation.
Conneally, J., Childs, C. & Walsh, J.

Tectonic Studies Group Annual Business Meeting
12.00 – 12.45

Lunch and poster session
12.45- 13.30

Session 6: **Fault Zones & Processes II**
Chair: Clare Bond
13.30 – 15.00

400,000 years of fault related and man-made leakage from an analogue for engineered geological storage of CO2.
Burnside, N., Shipton, Z., Ellam, R. & Dockrill, B.

Climate driven CO2-degassing from intracrustal faults.
Kampman, N., Burnside, N.M., Shipton, Z.K., Ellam, R.M., Chapman, H.J. & Bickle, M.J.

Improving side seal predictions on faults by integrating geometric and property uncertainty: Examples from well-constrained Gulf of Mexico fields.
Hemingway, D., Wood, V., Freeman, S., Smith, S. & Harris, S.

Damage zone/fault core; an unhelpful view of fault zone structure?
Childs, C., Manzocchi, T., Walsh J. & Schöpfer, M.

Damage zone evolution and permeability structure of segmented normal faults.
Rotevatn, A., Bastesen, E. & Fossen, H.

Posters and refreshments
15.00 – 15.30

Session 7: **Sedimentary Basin Structure**
Chair: Ian Vann
15.30 – 16.30

Multiphase Fault Evolution in a Rotational Margin Setting: Offshore Sirte Basin, Libya.
Maddock, P., McCaffrey, K., Imber, J. & Ceraldi, T.S.

Controls on the Lateral Variation in Structural Style Along an Evaporite-Influenced Normal Fault Array, Halten Terrace, Offshore Mid-Norway
Wilson, P., Elliott, G.M., Gawthorpe, R.L., Jackson, C. A-L., Michelsen, L. & Sharp, I.R.

The growth and linkage of salt-influenced extensional faults: Egersund Basin, Norwegian North Sea
Tvedt, A.B.M., Jackson, C. A-L., Rotevatn, A. & Gawthorpe, R.

Fault evolution during polyphase extension: Horda Platform, North Sea
Bell, R.E., A-L. Jackson, C. A-L., Whipp, P. & Clements, B.

KEYNOTE LECTURE
16.30 – 17:00
The role of structural geology in the past, present and future development of the UK Continental Shelf.
Dave Barr

Posters and refreshments
17:00 – 18.30

Conference dinner (Macdonald Holyrood Hotel)
19.00 onwards

Day 3 – Friday 6th January

Session 8: **Margins**
Chair: Simon Stewart
09.15 – 10.30

Landscape Evolution of Madagascar and Africa through the Cenozoic Era.
Paul, J.D., Roberts, G.G., White, N. & Wilson, J.

Modelling in-plane compression and thermal anomalies: Application to the post-rift evolution of the Rockall Trough
Smithells, R.A., Egan, S.S., Clarke, S., Kimbell, G., Hitchen, K. & Johnson, H.

Vertical stress magnitudes in the Northern Niger Delta Basin, Nigeria: The constraining factor for overpressure prediction.
Adewole, E., Healy, D. & Macdonald, D.

Structural styles of the Nankai Accretionary Prism, off SW Japan: comparisons of core, LWD and seismic data.
Yamada, Y., McNeill, L., Moore. J.C. & Nakamura, Y.

The deformation history of syn-orogenic foredeep basins as a clue for orogenic dynamics : a case from SW Tuscany, Northern Apennines, Italy
Tavarnelli, E.

Posters and refreshments
10.30 – 11.15

KEYNOTE LECTURE
11.15 – 11.45
A Balancing Act – a thirty year perspective
Alan Gibbs

Session 9: **Strike-slip and Oblique Tectonics**
Chair: David Iacopini
11.45 – 12.30.

Using high resolution multibeam bathymetry to analyse a strike-slip fault network.
Nixon, C.W., Sanderson, D.J. & Bull, J.M.

Flexural basin reworked by salt-related strike-slip termination pull-apart structures: the Adony Basin.
Palotai, M. & László Csontos, L.

Three-Dimensional Fold Geometries in N Iraq and SE Turkey: Oblique Collision between Arabia and Eurasia.
Jones, R., Pearce, M., Alsop, G.I. & Rock, G.

Lunch and discussion: **Structural Geology – what should we be teaching?**
Led by Roddy Muir.
12.30 – 13.45

Session 10: **Carbonate Fault Zones II**
Chair: Atle Rotevatn
13.45 – 15.00

Fracture sealing utilising microbially induced carbonate precipitation.
Moir, H., El Mountassir, G., Lunn, R.J. & Gilfillan, L.J.

Textural modification and deformation related to faulting in chalk rocks.
Vandycke S., Bergerat, F. & Baele, J-M.

Slip zone structure and processes in seismogenic carbonate faults.
Bullock, R., De Paola. N. & Holdsworth, R.E.

Experimental deformation of calcite fault gouges at high normal stress and sliding velocity.
Smith, S.A.F., Billi, A., Spagnuolo, E., Di Toro, G., Nielsen, S. & Violay, M.

The frictional properties of carbonate gouges at sub-seismic and seismic slip rates.
Faoro, I. & De Paola, N.

Refreshments (and poster clearance)
15.00 – 15.30

Session 11: **Fault Zones & Processes III**
Chair: John Wheeler
15.30 – 16.45

A comparison of cumulative vs. incremental fault growth derived from high-resolution LiDAR and InSAR data of the Dabbahu segment, Afar, Ethiopia.
Hofmann, B., Wright, T.J., Paton, D.A. & Rowland, J.V.

The role of reactivation and fluid pressure cycling in the development of late zeolite-bearing faults and fractures from the Adamello batholith, Italy.
Dempsey, E., Holdsworth, R.E.& Di Toro, G.

The evolution of fault zones in basalt: predicting internal structure, petrophysical properties and effect on fluid flow.
Ellen, R., Shipton, Z.K., Lunn, R.J. Lee, M. & Brown, D.J.

Fault zone architecture and permeability structure evolution in basalts.
Walker, R.J., Holdsworth, R.E., Armitage, P.J. & Faulkner, D.R.

Deriving fault slip histories from cosmogenic exposure ages along bedrock fault scarps.
Phillips, R.J., Cowie, P.A., Walker, M., Roberts G., Dunai, T., Zijerveld, L.J.J., Wilkinson, M., McCaffrey, K.J.W. & Bubeck, A.

Closing remarks:
16.45 – 17.00
John Wheeler (chair of TSG)

TSG 2012 Posters

(alphabetical by first author)

Landscape and tectonics of the Greater Caucasus.
Abduelmenam Alburki, K.J.W. McCaffrey & M.B. Allen.

Exploring the complex origins of orogenic plateau magmatism.
Mark B. Allen, Iain Neill, Monireh Kheirkhah, Jeroen van Hunen, Khachatur Meliksetian & Mohammad H. Emami.

Seiche-triggered deformation of offshore sediments.
G. Ian Alsop & Shmuel Marco.

Quantifying patterns of deformation bands: examples from the Hopeman Sandstone, Moray, Scotland.
Abdullah Awdal, Dave Healy & Ian Alsop.

Use of digital technology to aid 3D visualisation of Earth structures in the field and laboratory.
Clare E. Bond, Rob Butler & Roddy J. Muir.

Structural geology: *how* should we be teaching undergraduates?
Chambers, JA.

Investigating the controls on porosity and permeability development in unconventional igneous oil and gas reservoirs.
Colette Couves, Steve Roberts, Ian Troth, Andrew Racey & Angus Best.

Natural slip surfaces in fault cores of seismogenic carbonate faults.
N. De Paola, F. Agosta, F. Balsamo, R. Bullock, E. Dempsey, I. Faoro, R.E. Holdsworth & F. Storti.

The timing and controls of salt wall collapse in the Central Graben of the North Sea.
Andrew Emery, Hugh Beeley & Neil Grant.

Micromechanics of normal fault initiation: the Fasagh Fault Zone, NW Scotland.
Siân H. Evans & Geoffrey E. Lloyd.

Porosity around fault zones: correlations between fault zone architecture and petrophysical properties.
N.J.C. Farrell, M. Prieto, D. Healy, C.E. Bond & G.I. Alsop.

Investigating the glaciotectonic deformation of glacigenic materials through AMS.
Edward Fleming, Carl Stevenson, Doug Benn, Mike Hambrey, Mike Petronis & Ian Fairchild.

Characterising fracture systems within the Lewisian Gneiss Complex, northwest Scotland: An onshore analogue for the Clair Field.
Franklin, B. S. G., Martin, J. C., Holdsworth R. E., McCaffrey K.J. W., Krabbendam M., Conway A. & Jones R.

A combined rigid/deformable plate tectonic model for the evolution of the Indian Ocean.
Glover, C.T., Adriasola Munoz, A.C., Watson, J.G., Harris, J.P. & Goodrich, M.

Insights into the geometry of the Crozon fold-and-thrust belt of Central Armorica (Brittany, France).
Tom Haerinck, Timothy Debacker & Manuel Sintubin.

The quantification of fracture patterns.
Dave Healy.

A re-evaluation of the normally zoned Loch Doon Pluton, SW Scotland: implications for emplacement mechanisms.
Hines, R.

A new mechanism for silica gel precipitation along faults caused by fluid pressure drop associated with seismogenic slip.
Holdsworth, R.E., Lloyd, G.E. & Smith, S.

Seismic damage zones and their impact within thrust and fault imaging.
Iacopini D & Butler, R.

Insights into the Middle Pleistocene Anglian Glaciation through the magnetic analysis of diamicton.
Joseph Jennings, Edward Fleming & Carl Stevenson.

Displacement vector analysis: A new method for analysing cross-strike discontinuities and transverse zones.
Kelly, M.J., Williams, G.D., Clarke, S.M. & Leslie, A.G.

Using terrestrial laser scanning to investigate the joint pattern of a fractured carbonate reservoir analogue, Eifel, Germany.
Dennis Laux, Tomas Fernandez-Steeger & Christoph Hilgers.

Mid-crustal section of a crustal-scale shear zone (Malpica-Lamego Line, Variscan Orogen, NW Iberia).
Sergio Llana-Fúnez & Alberto Marcos.

Hinterland-propagation in the fold and thrust Loch Alsh sector of the Moine Thrust Belt, NW Scotland.

Leslie, A.G., Krabbendam, M. & Goodenough, K.M.

Emergent thrusts in the accretion history of the Monian (Penobscottian), outboard margin of East Avalonia.
Leslie, A.G., Schofield, D.I., Burt, C.E. & Morgan, D.

The effects of macro- and micro- scale deformation on zircon and its implications for studies of regional tectonics: examples from the Lewisian Gneiss Complex of Northwest Scotland.
John MacDonald, John Wheeler, Elisabetta Mariani, Kathryn Goodenough, Simon Harley & Quentin Crowley.

Fabrics produced mimetically during static metamorphism: retrogressed eclogites from the Zermatt-Saas zone, Western Alps, as an example
D. McNamara, M. Pearce, J. Wheeler & D. J. Prior

Quantification of uncertainty in geoscience interpretation: revealing the factors that affect interpretational ability.
Euan Macrae, Clare Bond, Zoe Shipton & Rebecca Lunn.

Architecture of fault zones in carbonates.
E. A. H. Michie, T. J. Haines, D. Healy, G. I. Alsop, J. Neilson & N. E. Timms.

Critical State Soil Mechanics: Can this be used to predict fault zone architectures?
E. A. H. Michie, D. Healy, G. I. Alsop & N. E. Timms.

3D structural model-building and fold construction using a digital dip isogon construction method: The Mt. Lykaion (Greece) Sanctuary of Zeus case study.
Moccia, A., Similox-Tohon, D., Clelland, S. & Davis, G. H.

Channel flow extrusion model to constrain viscosity and Prandtl number of the Higher Himalayan Shear Zone.
Soumyajit Mukherjee.

Crystallization-force experiments in porous microreactors.
Jan Niederau & Christoph Hilgers.

Quaternary tectonic uplift of the Kyrenia Range, northern Cyprus: preliminary field results and objectives.
Romesh N. Palamakumbura, Alastair H. F. Robertson, Hugh D. Sinclair, Dick Kroon, Mehmet Necdet.

Sensitivity of elastic waves to hydro-mechanical variations of fault zones: an experimental approach.
Joachim Place, Oshaine Blake & Dan Faulkner.

Intrusive peridotites and granites exhumed on Seram and Ambon, eastern Indonesia during Banda Arc subduction rollback.
Jonathan M. Pownall, Robert Hall, and Ian M. Watkinson.

Constraints on 3D fault and fracture distribution in basalt-clastic sequences from terrestrial laser scan (LiDAR) datasets: Faroe Islands.
Bansri G. Raithatha, K.J.W. McCaffrey, R.J. Walker and G. Pickering.

Development of crestal collapse structures above dissolving salt anticlines: Application to seismic Interpretation within salt-controlled basins.
Tom Randles, Stuart Clarke and Phil Richards.

The Eurekan Orogeny: the tectonic culmination of the Sverdrup Basin, Canadian Arctic Islands.
Stephen Rippington, Helen Smyth & Robert Scott.

Tectonics, structure, and hydrocarbon potential of the Mexican Ridges fold belt, western Gulf of Mexico.
Luis E Salomón-Mora, Ian Alsop, Stuart Archer & Miguel Cruz-Mercado.

Implications of petrostructural analysis for the tectonic evolution of the Neoproterozoic Tasriwine ophiolite (Anti-Atlas, Morocco)
Triantafyllou, A., Berger, J., Diot, H., Ennih, N., Plissart, G., Sterckx, S.

Seismic imaging of salt diapir flanks constrained by outcrop data.
Liliana Vargas-Meleza, David Healy & Ian Alsop.

Composition and origin of exotic, fault-related intrusions, Karakoram Fault, Ladakh.
H. Watkins.

Partitioning of lithosphere stretching and thinning at continental rifted margins: Norwegian margin study.
Watson, J.G., Kusznir, N. J. & Roberts, A.M.

Determining relay zone linkage geometry for faults close to seismic resolution.
Alan Wood, Richard Collier & Douglas Paton.

Information for speakers

All presentations (except keynotes) have a strict allocation of 15 minutes. You should aim to speak for no more than **12 minutes**, allowing time for questions. This is most important – the TSG Annual Meeting is a discussion forum. Session chairs will be asked to enforce these times strictly. Keynote speakers should aim to speak for no more than 25 minutes, with 5 minutes for discussion.

We will run all talks from a central PC using **Powerpoint** 2007. Please ensure that your presentation is compatible with this. Take special care with embedded video clips. Note speakers will not be able to use their own lap-tops to give presentations. All talks must be uploaded well before the interval before the programmed delivery time. All presentations will be erased from the PC at the end of the conference.

Information for poster presentations.

Posters are a key part of the TSG Annual Meeting and are given pride of place in the schedule. They remain up for the duration of the conference. Catering will be provided during the poster sessions. To promote discussion, posters will be grouped into themes by the organizing committee. Each display will be up to **A0 – portrait**. A successful poster should be readable from at least 1 metre away. They should be based on illustrations. Text (including on diagrams) should be no smaller than 20 pt, with important text at 36 pt or greater. You may find it useful to include your photograph on the poster, so that participants can find you for discussion.

Posters should be set up from 10.00 and certainly before the first poster session (12.45) on Wednesday 4th Jan. They should remain up for the entire conference – but be removed by the end of the final interval (15.30 on the 6th). The organisers take no responsibility for posters left up beyond this period. The poster boards will be removed during the final session of talks.

Abstracts of Oral Presentations

Proglacial to subglacial deformation and permafrost-glacier interactions associated with a Pleistocene ice sheet margin

Emrys Phillips[1]*, Richard Waller[2], Jonathan Lee[3] and Julian Murton[4]

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Abstract

Analysis of the stratigraphy and structures developed within polydeformed sediments exposed in the coastal section between West Runton and Weybourne (eastern England) reveals the glacitectonic signature associated with the advance of a major Mid-Pleistocene (Anglian) ice sheet. The sequence of pre-glacial deposits and glacial sediments laid down during earlier southerly directed ice advances (A1 to A4) was deformed and disrupted by ice advancing from the west/southwest (A5), marking a major change in ice flow dynamics in northern East Anglia. Proglacial deformation associated with this progressive proglacial to subglacial deformation event occurred well in advance of the ice margin and was dominated by thrusting. Morainic ridges which developed above the propagating thrusts controlled sediment dispersal patterns within outwash sandur, leading to the formation of small sub-basins in the foreland. Ice-marginal deformation, characterised by thrusting and large-scale folding, led to the stacking of material and the development of a large push moraine complex. Submarginal to subglacial deformation was highly variable in its style and intensity, ranging from heterogeneous folding and thrusting, through to more pervasive ductile shearing and the formation of a 15 to 20 m thick glacitectonic mélange. The later contains large (up to 50 m in length) rafts of chalk bedrock and pre-glacial sediments, as well as smaller intraclasts (up to 10 m in length) of unconsolidated sand and gravel. These intraclasts, which contain well-preserved primary sedimentary structures, are attributed to overriding, deformation and incorporation of permafrozen sediment into the bed of the advancing ice sheet. Deformation within the permafrost bed occurred at temperatures slightly below the pressure-melting point of ice (i.e. 'warm permafrost'), preserving the pore ice cement within the sand intraclasts, which consequently acted as rigid bodies within the deforming (ductile) and partially frozen fine-grained matrix of the mélange. The eventual development of a system of subglacial drainage channels beneath the ice sheet during the later stages of ice advance led directly to an increase in the efficiency of the subglacial hydrogeological system. This resulted in the draining of the bed of the ice sheet and a change from earlier ductile deformation, to more brittle thrusting associated with the locking up of the subglacial shear zone and the potential cessation of ice sheet advance.

Branching shear zones – examples from Saudi Arabia

Sven Meyer, Cees Passchier

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Ductile shear zones are usually imagined as straight disc shaped high strain domains with simple gradients of vorticity and strain. Most shear zones, however, have a more complex geometry and are part of a network of interconnected zones of variable orientation. The Arabian Nubian shield in Saudi Arabia contains interesting examples of complex, branching shear zones that are developed in Neoproterozoic arc-related metavolcanic and intrusive rocks. These Neoproterozoic shear zones are part of the Najd fault system. Two zones are the focus of this study.
The 3 km wide amphibolite grade Ajaj shear zone is a sinistral strike slip zone which splits into two branches of opposite shear sense. The kinematic arrangement of the branches is such, that they form a so-called zipper shear zone system, where a triangular block is expelled between two strike slip shear zones branches, which join to form single zone with complex internal flow.
100 km north of the Ajaj zone, the Qazaz complex (Figure 1) is a triangular dome of flat lying to steep shear zones with mostly shallowly plunging lineations. This zone is similar to a metamorphic core complex, with migmatites in the core, and low grade sediments outside the shearzone screen. To the north, the core complex grades into a 200 km long antiformal strike slip shear zone, the 5 km wide Qazaz zone. This major strike slip zone ends in the Qazaz triangle, and most of its displacement seems to be accommodated there.

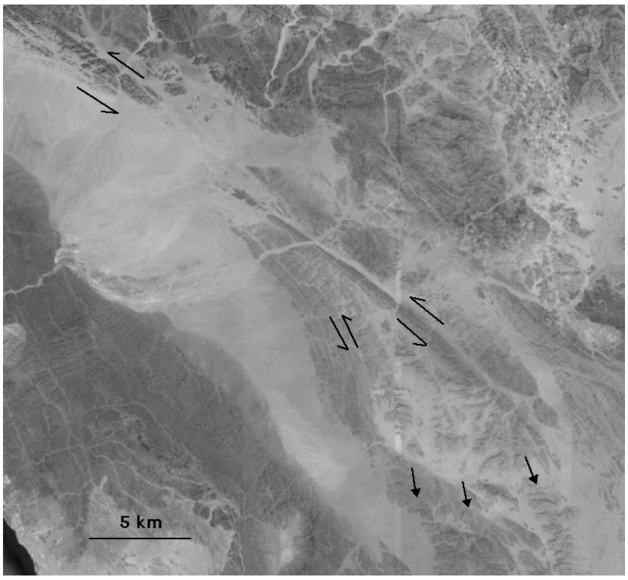

Figure 1: Qazaz complex with bounded by a shallowly dipping normal shear zone in the south, and sinistral strike slip shear zones along its sides. The zone has high-grade orthogneiss in the core, and low-grade sediments to the south and west. It grades into a crustal-scale strike slip shear zone to the NW

Stress directions and magnitudes derived from Stylolites

[1]Koehn Daniel; [2]Renaud Toussaint; [3]Marcus Ebner; [4]Paul Bons; [5]Fiona Kulzer

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[4]University of Tübingen, Germany
[5]University of Mainz, Germany

Recent observations have shown that stylolites (rough dissolution seams in rocks) can be used to determine the direction and magnitude of overburden or tectonic stress that existed while the structures developed. Since stylolites are common features in sedimentary basins and fold and thrust belts they are ideal as paleo-stress gauges. Stylolites develop during localized dissolution of the host-rock and show a pronounced roughness with spikes or teeth. The use of the teeth orientation to determine the direction of the main compressive stress is a common practice in structural analysis. If the roughness is analysed in detail it can also be used to determine the product of the differential and mean stress. Stylolites develop a different roughness on small-scale (below about 1mm) versus large-scale regimes. In the small-scale regime the roughness is influenced by surface energies that result in a roughness with a Hurst exponent of about 1.0, meaning that the wavelength-amplitude ratio is constant on several scales. On the large-scale elastic energies dominate the roughening process leading to a surface with a Hurst exponent of about 0.5 so that the surface is rough on small scales but flat on large scales. The position of the cross-over between the two scaling regimes changes as a function of the mean and differential stress on the stylolite. With a number of assumptions the full paleo-stress tensor may be determined from sedimentary as well as tectonic stylolites. We will show applications where stresses are determined in sedimentary basins and fold and thrust belts and will discuss the stress-inversion method in detail. We show how overburden stress in a sedimentary basin can be calculated, how stress measurements on stylolites change across major basin faults and how tectonic stress tensors can be derived.

Structural control of the copper-cobalt grade distribution at the Konkola ore deposit, Zambia

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The Konkola ore deposit is a high grade stratiform copper-cobalt deposit in northern Zambia, forming part of the Central African Copperbelt. The Konkola ore deposit contains 8.1Mt of resources at an average grade of 3.6wt% Cu, placing it in the highest grade mines of the world. The economic ore is confined to the Ore Shale Formation, part of the Neoproterozoic Katangan Supergroup. These predominantly siliciclastic to carbonaceous sediments were deposited in a continental rift which evolved into a proto-oceanic rift. During the Neoproterozoic to early Phanerozoic Lufilian orogeny, these sediments were deformed under lower greenschist facies metamorphic conditions. The copper-cobalt ore occurs (1) disseminated in the host rock, (2) in diagenetic quartz lenses and layers or (3) in layer-parallel and irregular veins. The ore mineralogy consists of chalcopyrite, bornite, chalcocite and minor carrolite. The different occurrences indicate significant ore remobilization during and after the main stages of the Lufilian orogeny.

The ore deposit is draped around the hinge zone of the gently NW-plunging Kirilabombwe antiform. Several fault zones have been identified at the Konkola mine: one fault zone runs parallel to the axial plane of the Kirilabombwe antiform and two major fault zones, having throws of up to several tens of meters, are present in the southern limb of the antiform. Copper and cobalt grade maps were produced to assess the effect of these large-scale structural features on the occurrence and grade of the ore. These maps contain 1458 data points of mainly borehole assay results averaged over the length of the Ore Shale Formation, producing a 3D view of the ore grade.

Results show that total copper contents are much higher (>5wt%) compared to average values in the mine, in the hinge zone of the Kirilabombwe antiform and in the proximity of the fault zones in the southern limb. Copper content is diminishing with increasing distance over several hundreds of meters away from the fault parallel to the axial plane to values of <2wt% copper. All fault zones have a marked influence on the total cobalt concentrations. Cobalt is severely leached (<0.03wt%) in the proximity of the fault zones (~50m) whereas average concentrations in the mineralized areas are higher than 0.05wt%. This study shows that there is a significant structural control on the ore grade distribution. This suggests that these structural features played a significant role in the remobilization and subsequent concentration of the metals.

How to form folds with convergent cleavage fans in pelites

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In a fold, convergent cleavage fanning is generally associated with relatively competent beds and divergent cleavage fanning with relatively incompetent beds. Still, folds with pronounced convergent cleavage fans frequently occur within Silurian pelites of the single-phase deformed Anglo-Brabant Deformation Belt. These fans have classically been attributed to two consecutive deformation phases. However, there is no evidence for a poly-phase deformation.

A relationship exists between degree of convergent cleavage fanning on the one hand and fold interlimb angle and fold wavelength on the other hand. Small-scale parasitic folds never show a convergent cleavage fanning, whereas for the larger folds the degree of fanning increases with fold wavelength and with decreasing fold interlimb angle. The degree of convergent cleavage fanning also changes across formation boundaries and in relation to lateral changes in bed thickness.

It is essentially the homogenous, fine-grained lithology that is responsible for the convergent cleavage fan development. This specific lithology, with very thin and isolated competent units, resulted in a large amount of pre-buckle, layer-parallel shortening, eventually resulting in the formation of convergent cleavage fans during buckling.

The formation of the convergent cleavage fans is an example of tectonics controlling the nature of the sediments, and the resulting deposits in turn influencing local and regional deformation geometries. In addition, it serves as an example of the relatively poorly documented concept of multilayer folding of predominantly pelitic, “statistically homogenous” sequences without obvious “control units”.

Stress inversion and tensor separation using OFA-clustering – a test on artificial and real data

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We propose a method for stress inversion and separation of principal stress directions from heterogeneous fault-slip data. The method builds on hard division in stress space by solving the Objective Function Algorithm (OFA), and will be referred to as OFA-clustering. For perfect generated datasets the OFA easily reaches its minima, the heterogeneous datasets are correctly separated and the resolved stress tensors calculated. However, as random errors are progressively introduced in the generated datasets the OFA fails in reaching its minima and the calculated stress tensors, corresponding to the lowest obtained value of the OFA (i.e. local minima), do not approximate the resolved stress tensors. To tackle this problem we grid all calculated principal stress orientations, corresponding with local minima of the OFA lower than the mean value, after e.g. 1000 runs. We show that clusters of principal stress orientations, when plotted in a stereonet, correspond well with the orientations of principal stresses used to generate the resolved stress tensors.

The method is tested on a real dataset from the Gullkista Fault in North Norway. This fault is a prominent normal fault exposed in crystalline basement rocks in a quarry at Røsand. The fault core consists of a thick zone of cataclastites containing abundant slickensided fracture planes. However, sense of slip is often difficult to assess due to the lack of offset markers. Solving the OFA for one to four stress tensors produces unrealistic results using the tensors corresponding to the minimum obtained value of the OFA. On the other hand the OFA-clustering technique produces realistic results with principal stress directions in agreement with the orientation and slip direction of the main fault plane. Consequently the proposed method of stress inversion and tensor separation using OFA-clustering gives reliable results both for generated and real datasets. The method is especially useful in areas where fault slip sense is difficult to assess as the inversion and separation only requires the orientation of the slip vector, not slip sense.

Deformation Structures associated with the emplacement of high level intrusions, Henry Mountains, Utah

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High-level sill and laccolith complexes comprise an important part of sub-volcanic plumbing systems in which magma is emplaced as a series of sub-horizontal tabular sheet-like intrusions. Most studies have focused on the internal architecture of these intrusions, while only a few have looked in detail at the host rock and how the additional volume of rock is accommodated within the crust, i.e. the 'space problem'. The aim of this study is to develop an understanding of the stages of emplacement and the internal textural evolution of Tertiary sills and laccolith intrusions in the Henry Mountains. The research project is twofold: firstly, to carry out kinematic and geometrical studies of the emplacement-related structures in the host rocks to several of the satellite intrusions to the Mt. Hilliers intrusive centre; and secondly, to carry out micro-scale textural and geochemical studies of plagioclase-feldspar and amphibole phenocryst populations preserved within the intrusions.
Fieldwork to date has focused on two satellite intrusions to Mt. Hilliers: Trachyte Mesa (the most distal intrusion, simple geometries); and Maiden Creek (closer to Mt. Hilliers, more complex geometries) both of which are emplaced into the Entrada Formation sandstone.
Trachyte Mesa is an elongate (NE-SW) laccolith concordant with the Entrada sandstone it intrudes. Two structural transects across the north-west lateral margin have identified distinct structural domains that reflect both temporal and kinematic variations in deformation. Three phases are identified. A background set of small, regionally pervasive normal faults (Phase 1) were identified across the entire area. Phase 2 is characterised by conjugate deformation bands and increase in intensity and spacing up the flank of the intrusion. Within this same zone a series of calcite filled normal faults that parallel the margin of the intrusive body can be found. Due to their spatial, kinematic and overprinting relationships we interpret these to be linked to the emplacement of the intrusive body. Finally overprinting all other structures we see mode 1 joints (Phase 3) which are likely to be late-stage structures related to relaxation of the host rocks and are most common over the upper portion of the intrusion.
Maiden Creek is characterised as a sill with a complex elliptical body with several finger-like lobes. Detailed outcrop studies across two neighbouring lobes have identified a sub-horizontal shear zone which may be traced from the top of each intrusive lobe and separates low-moderately deformed sandstones from highly deformed sandstones trapped between the two lobes. This shear zone appears to have played a critical role in the accommodating the volumetric change associated with the intrusion.

Cambrian successions and detrital zircon geochronology of Megumia: southern Nova Scotia and North Wales as dispersed fragments of a peri-Gondwanan basin.

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The Harlech Dome and St. Tudwell's Peninsula, in North Wales, and the Meguma Terrane of southern Nova Scotia, in Atlantic Canada, preserve similar sedimentary successions of Cambrian age. All three areas display thick early Cambrian continentally-derived sandstone turbidites, overlain by early to middle Cambrian alternating mud-rich and sand-rich units in which manganese is concentrated. The manganiferous interval is everywhere marked by a diverse and abundant assemblage of trace fossils, including locally abundant *Teichichnus*. Above, the successions comprise anoxic, organic-rich turbidites, shallowing upward into paler, early Ordovician mudstone and siltstone with the graptolite *Rhabdinopora*. The succession at St. Tudwell's is the thinnest of the three and displays a shallowing event close to the base of the Furongian (upper Cambrian) marked by a disconformity.

Meguma detrital zircon assemblages display strong peaks in the late Neoproterozoic (common to many peri-Gondwanan terranes) and in the Paleoproterozoic (2.0 - 2.2 Ma), suggesting derivation from the Eburnean orogens of west Africa. Detrital zircons from the Harlech Dome succession reveal closely similar clusters of ages.

Within the limited constraints of the available biostratigraphic and geochronologic data, major changes in environment occurred synchronously in the two successions until the Early Tremadoc. Thereafter the histories diverge. The highest parts of the Nova Scotian succession record shallowing conditions with shelf sedimentation extending through the Early Ordovician, whereas the Welsh successions are overlain with angular unconformity by Tremadoc volcanics, and then by Floian sandstones and younger Ordovician volcanics. Overall, the Cambrian successions in these areas show much greater similarity to each other than to adjacent successions in "Avalonia", suggesting proximity between the two terranes on the margin of Gondwana. We suggest the term "Megumia" for a paleogeographic domain that included these successions, which were dispersed during subsequent Appalachian/Caledonian movements, starting with the Penobscot and Monian events in the Early Ordovician.

A late-Ordovician 'Tornquist' supra-subduction shear zone system on the NE margin of Eastern Avalonia: the Caledonides of N & E England

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North of the Variscan Front, UK fault patterns, e.g. as shown on the BGS tectonic map of the UK, display intriguingly systematic arrangements that invite inquiry as to their origin and degree of fundamental basement control. Analysis of potential field data by, among others, Lee et al (1990) reveals a similar, systematic arrangement of roughly E-W and NW-SE-trending regional geophysical anomalies, and an *en-echelon* arrangement of buried plutons of known and inferred Caradoc age. There has been speculation with regard to the origin, timing and temporal relationships of these structures and anomalies, as they pertain to the Caledonides of N and E England. For example, a significant part of the Caledonide structural architecture has been ascribed to Acadian deformation, resulting from closure of the Iapetus Ocean, deforming an earlier system of Ordovician sedimentary and arc volcanic rocks. We propose that, when the regional fault and geophysical data are taken together, they can be interpreted more simply in terms of a coherent, crustal-scale, dextral shear system in a volcanic arc, located in the over-riding plate above a NW-SE 'Tornquist' suture. Amongst others, the Puysegur Ridge and Trench system off South Island, New Zealand provides a very attractive modern analogue. Acadian and other subsequent deformation events reactivated these earlier structures.
If accepted, this model has potential consequences for the NW-SE trending Caledonides of Wales; regional fault patterns again invite speculation. For example, why does the NE-trending structural grain as manifest in the long-lived Welsh Borderland Fault System appear *not* to extend further NE than the tip of the Midlands Microcraton (MMC), but instead *appear* to turn through 90°, to trend NW through NW England? Why does this alignment appear to coincide with the known location of the NE margin of the MMC and, when projected, pass immediately SW of the Lake District? Is there a NW-trending deep crustal lineament parallel to, and in line with the NE margin of the MMC. The Ordovician 'Tornquist' shear system established an architectural template that has underpinned structural development on N and Eastern England since then, influencing particularly the location and character of Carboniferous blocks and basins.

Reference

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Monian (Penobscottian) thrust tectonics on the outboard margin of East Avalonia

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The island of Anglesey, north Wales, comprises a complex collage of Late Neoproterozoic and Palaeozoic rocks that preserve a record of accretion processes on the outboard margin of Gondwana. Late Neoproterozoic subduction of Panthalassa/palaeo-Pacific crust is recorded by the intrusion of the Coedana Granite at 615 Ma, part of an assemblage of supra-subduction zone granites that make up much of East Avalonia, and by the accretion of blueschists of the Penmynydd Zone, illustrating metamorphic closure at around 560 Ma. However, we consider much of the present architecture of the island to reflect protracted accretion tectonics commencing with Early Ordovician (Monian/Penobscottian) thrusting and assembly of the Late Neoproterozoic rocks along with the Middle Cambrian to Early Ordovician Monian Supergroup meta-sedimentary succession.

South- or SE-directed translation accompanied low greenschist facies metamorphism and strong non-coaxial ductile to brittle-ductile strain preserved in the upper parts of the New Harbour Group. New field observations indicate that this is unconformably overlain by olistrostomal deposits of the Gwna Group, here interpreted as a molasse deposit reworking uplifted Late Neoproterozoic shelf. Renewed late Arenig subsidence gave rise to development of a Middle Ordovician to early Silurian marine foreland basin. That basin is characterised by a strongly asymmetric geometry with foreland migration of basinal facies interpreted as reflecting continued horizontal translation through the Middle Ordovician.

Ordovician and Silurian stratigraphical elements juxtaposed with the basement Coedana Complex are imbricated along new thrust faults that record shortening by SSE-directed horizontal translation during a post-Llandovery phase of ductile, brittle-ductile and brittle deformation. Latest phases of translation are recorded in the development of axially sourced fluvial system of the Old Red sandstone on Anglesey, emplacement of thrust klippen onto the ORS and development of new molasse deposits.

Onset of deformation during the mid-Arenig in Anglesey is consistent with Penobscottian accretion in the northern Appalachians. Here, advancing subduction is accompanied by arc-ophiolite obduction onto the Gander margin (Moninan Supergroup equivalent) prior to renewed roll-back and development of new arc and back arc successions. In contrast, Anglesey records translation of Gander margin sediments onto in-board, East Avalonian basement with continued, albeit probably punctuated translation continuing through Silurian, even Early Devonian times.

A Caribbean-style plate in the Iapetus Ocean?

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Subduction of the Paleozoic Iapetus Ocean began relatively soon after its opening during the last stages in the break-up of Rodinia. Although estimates of the timing of break-up have varied, the earliest sedimentary rocks in the post-rift succession on the Laurentian margin date from the Bonnia-Olenellus zone at the top of proposed Cambrian series 2, and are younger than 515 Ma. Vestiges of the Iapetan oceanic lithosphere are preserved as supra-subduction zone ophiolites and related mafic complexes in the Appalachian-Caledonian orogen. The earliest indications of subduction are recorded in arc rocks preserved in ophiolites less than 20 million years younger than the end of Iapetan rifting. The earliest collisional events are recorded almost simultaneously in elements of the Laurentian and peri-Gondwanan margins during the Early Ordovician, between 490 and 480 Ma, and led to the development of active continental margins on both sides of the young ocean, in most reconstructions. Closure of the ocean between Avalonia and Laurentia was complete by about 425 Ma. Compared with the modern Atlantic, the Iapetus Ocean was very short-lived.

Available Sm-Nd isotopic data indicate that the mantle source of Iapetan ophiolitic complexes was highly depleted as a result of a history of magmatism that occurred before the Iapetus Ocean existed. We propose that this oceanic lithosphere was captured from the adjacent Palaeopacific lithosphere very early in the history of Iapetus, in a manner analogous to the proposed Mesozoic-Cenozoic “capture” in the Atlantic realm of the Caribbean plate. The early phase of magmatism rendered it more buoyant than surrounding asthenosphere, which facilitated its preservation, implying that highly depleted mantle may be preferentially preserved in the geologic record. This hypothesis may help to explain the initiation of subduction and the premature closing of the Iapetus Ocean, the timing of the earliest collisional events, and the distribution of peri-Gondwanan terranes in the Appalachian-Caledonian orogen.

RECONSTRUCTION OF THE KINEMATIC EVOLUTION OF THE NORTH-ARMORICAN SHEAR ZONE, BRITTANY, FRANCE

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The *North-Armorican shear zone* (NASZ) is assumed to be a through-going, east-west oriented, dextral transcurrent shear zone, that crosscuts the Palaeozoic Armorican massif in the north. However, a detailed paleostress analysis on faults observed in the Queffleuth cataclastic zone (QCZ), reveals stress states that indicate both, dextral and sinistral kinematics. In the QCZ, four morphological classes of faults are observed. Class A can directly be linked with cataclasis, as the matrix-to-clast ratio increases and clast size decreases towards the faults. Classes B, C and D crosscut the cataclasitic rocks. The crosscutting nature indicates that the fault activity must have taken place at the end of the cataclastic deformation. In thin sections of the cataclasites, both dextral and sinistral shear sense indicators are observed (figure). Paleostress analysis reveals five distinct stress states. Each of the morphological classes cannot be attributed to a single stress state, so that no correlation between the fabric of the faults and the stress states is apparent. Stress states 3 and 4 indicate dextral kinematics and can be related to the main dextral shear activity of the NASZ. Stress states 1 and 2 are thought to be precursors of the main activity. Possibly, the deformation during these stages took place in the ductile regime, during which the trend of the maximum horizontal stress oscillated between ESE and SSE. Additionally, a sinistral activity is inferred from stress state 5. The latter can be seen as a relaxation event predating or postdating the main activity. A cyclic evolution between dextral and sinistral kinematics cannot be excluded. Based on our study, two characteristics of the NASZ, commonly described in literature, need reassessment. Firstly, our study shows that the rocks in the QCZ are protocataclasites to cataclasites, in contrast to the ultramylonites indicated on the geological map (Cabanis et al., 1981). Secondly, a sinistral activity is inferred for the NASZ, which has never been demonstrated in literature to date.

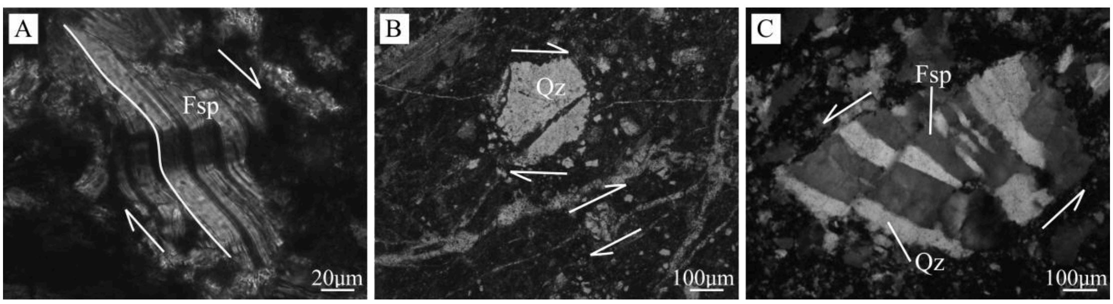

Figure: Optical microscope photographs of shear sense indicators. Bent twins in feldspar (Fsp) (A), δ-type winged mantled quartz (Qz) (B) and a fragmented and displaced clast (C).

Cross-strike Discontinuities: The development of the Loch Maree Transverse Zone

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Numerous authors have reported on geometry, kinematics and mechanics within fold-and-thrust belts. Whilst many works have dealt with palinspastic reconstructions and transport-direction-parallel balanced cross-sections, far fewer have focussed on three-dimensional architecture of fold-and-thrust belts, or examined how lateral variations in thrust architecture in different segments of thrust belts are linked via so-called 'transverse zones'. Systematic alignments on these lateral structures are suggested to include; sub-décollement basement faults, pre-thrusting cover strata deformation above basement faults, development of duplex structures/antiformal stacks, and/or along-strike variations in mechanical stratigraphy. Project methodologies incorporate a new study of a previously-researched sector of the Moine Thrust Belt, namely, the Achnashellach Culmination and the Loch Maree Fault Zone in the Kinlochewe district of the NW Highlands.

Previous work within the northern sections of the Achnashellach Culmination, towards the Loch Maree Fault (LMF) defines a structure developed in Cambrian quartzites and Torridonian sandstones. Distinct structural changes from north to south were recognised across the LMF at the northern termination of the culmination. New (2009 to 2011) detailed fieldwork along the north and south walls of the LMF at Kinlochewe has allowed the generation of new transport-direction-parallel/transport-lateral cross-sections and supported branch-line/displacement vector analysis across the northern termination of the culmination.

A thrust dominated region of overturned Torridonian/Lewisian, overlying a right-way-up Cambrian succession can be clearly identified on the northern wall of the LMF, compared to a fold-and-thrust dominated section on the southern wall of the LMF. That section identifies a 'thin flap' of pipe rock/basal quartzite imbricates to the south-east of the Meall a' Ghuibhais Klippe. This develops towards the hinterland into much thicker imbricate slices of pipe rock and Torridonian that can be traced farther south within the culmination into the Beinn Eighe region. Distinct compartmentalisation of the Moine Thrust Belt architecture is thus apparent across the LMF. The compartmentalisation is suggested to be a response to a step in basement that generated a transport-parallel lateral ramp or sidewall during thrusting. This transverse zone marks a change to the fold-and-thrust architecture of the southern sector of the Moine Thrust Belt (Leslie and Krabbendam, this conference)

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

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In the past, fault seal analysis has 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.

Macro-scale section analysis, balance restoration and 3D modelling 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.

Meso-scale detailed structural maps of exceptionally well-exposed outcrops are used to extract information on fault geometry. Models are proposed to define the elements of fault zones. Fault evolutions of typical outcrops are conducted in order to understand the dynamic process of the fault development.

Micro-structural analysis (e.g. SEM) and petro-physical 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 behaviour, and aims to identify the critical parameters that contribute to improving fault seal analysis in thrust systems.

Micro-geodynamics of the Karakoram fault zone, Ladakh, NW Himalaya

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Strike-slip fault zones are common structures in continental orogenic systems (e.g. Karakoram, Altyn Tagh, San Andreas and S. Alpine faults). Understanding their structure, deformation processes and strain distribution is fundamental to characterising how continental crust responds to orogenic stresses. However, understanding of the spatial distribution of strain accommodation in strike-slip fault zones and its evolution through time are incomplete.

The 800 km long dextral strike-slip Karakoram Fault Zone (KFZ), NW Himalaya, exhibits a wide range of fault rocks from mylonites to fault gouges, that are inferred to have formed over a range of palaeo-depth intervals during exhumation. The KFZ provides therefore an opportunity to investigate fault zone structure and strain distribution at varying depths within the continental crust. Field evidence suggests that deformation focussed on multiple strands of highly strained fault rocks separated by less deformed rock. The strain distribution and timing of deformation relative to exhumation across these strands has not previously been quantified.

This study combines field observations with optical and scanning electron microscopy to investigate the deformation processes and strain distribution along several transects that cross the KFZ. Initial results are presented from a 5 km transect that records strain variation in a suite of marbles adjacent to one strand of the KFZ. The determination of strain profiles for these exhumed KFZ fault rocks provides an analogue for understanding deformation at depth in active strike-slip fault zones.

The timing and structural style of the India-Asia collision from plate kinematic and seismic observations in the Equatorial Indian Ocean.

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The far-field signature of the India-Asia collision and history of uplift in Tibet is recorded by sediment input into the Indian Ocean and the strain accumulation history across the diffuse plate boundary between the Indian and Capricorn plates. We describe the history of India-Capricorn convergence from updated estimates of India-Somalia-Capricorn plate rotations and observations derived from seismic reflection data. New India-Capricorn plate rotations for the past 20 Myr are consistent with slow N-S convergence from 18 Ma about a stationary or nearly stationary pole near the eastern edge of the Chagos-Laccadive ridge, simpler than predicted by previous models based on many fewer data. The new rotations suggest that convergence began between 14 Ma and 18 Ma, consistent with marine seismic evidence for an onset of deformation at 15.4 – 13.9 Ma. They further show that convergence rates doubled at 8 Ma, in agreement with a sharp increase in fault activity at 8 – 7.5 Ma seen on seismic reflection profiles. In this presentation the style of deformation within the diffuse plate boundary will be reviewed, and the fit to a transpressional model discussed.

Using isotope geochemistry to unravel the mysteries of the Main Central Thrust, Sikkim Himalaya

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The Main Central Thrust (MCT) is a major Himalayan fault which is thought to have accounted for >150km of movement during the Himalayan orogeny[1] and plays a pivotal role in tectonic exhumation models such as channel flow[2] and wedge extrusion[3]. Unlike thrusts characterised by mainly brittle deformation, such as the Moine thrust, the deformation associated with the MCT spans several kilometres and is best described as a ductile ‘zone’. Despite its importance in Himalayan tectonic evolution, its precise location remains disputed in many transects[4]. In this study of the high strain deformation in Sikkim, samples have been collected from the zone of ductile deformation broadly coinciding with the MCT in order to investigate the location and rates of movement of this structure.

Previously, the term ‘Main Central Thrust’ has been used to refer to two distinct phenomena: 1) a thrust fault and 2) a protolith boundary between the Greater Himalayan Series (GHS) from the Lesser Himalayan Series (LHS). There is general consensus that each of these lithological packages is characterised by distinctive geochronological and chemical signatures. The LHS is a Palaeoproterozoic sequence with an εNd signature of -20 to -25, which has been intruded by ~1.8 Ga granites, whereas the GHS is a Neoproterozoic-Early Palaeozoic sequence, with an εNd signature of -15 to -20, typically intruded by ~500 Ma granites[5,6]. The protolith boundary can therefore be ‘mapped’ using isotope geochemical/geochronological data.

This paper will present the first combined U-Pb zircon geochronology and εNd isotopic study in Sikkim. These data will be used to determine the provenance of the rocks within the MCT zone in Sikkim, and whether the protolith boundary is located 1) within the high strain zone, 2) outside the high strain zone or 3) whether the MCT zone represents a zone of mixed isotopic signature due to tectonic interleaving during thrusting. This paper will further discuss whether, at least in Sikkim, there needs to be revision of the overall general use of the term ‘MCT’ to describe both the structural and the lithological boundary.

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Tectonics of the eastern Himalaya: U(-Th)-Pb geochronology of structures in Bhutan

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The tectonic evolution of the eastern portion of the Himalaya has been thrown into sharp relief by recent geological research in Bhutan. The Bhutan Himalaya is a unique sector of the orogenic front, distinguished by the presence of several klippen, a major out-of-sequence thrust fault and an apparently thickened, exhumed high grade core (the Greater Himalayan Sequence or GHS). Recent mapping and geochronological studies have shed new light on the structure and tectonics of this region. Unravelling the tectonic history here is crucial for understanding both heterogeneity and diachroneity of exhumation across the Himalaya.

Major north-west verging nappe folds in Tethyan clastic and carbonate sediments have been mapped across central Bhutan. Three, formally separated klippen have been re-mapped and re-interpreted as a single large allochthon that structurally overlies migmatitic gneiss and leucogranite of the high grade GHS. U-Pb dating of zircons in an ashbed within this allochthon and from a cross-cutting leucogranite dyke constrain the timing of the folds and provide insights into the deformation.

An E-W divide in tectonic regime along the Himalaya has been proposed[1], partly on the basis of a 12.5 ± 0.4 Ma High Himalayan granite in NE Bhutan, which is much younger than equivalent granites to the west of Bhutan (19-24 Ma). However in this study the ~80km x 10-50km Gophu la granite underlying the macroscopic folds in north central Bhutan yielded U-Pb zircon crystallisation ages and U-Th-Pb monazite ages of ~20Ma, consistent with most Tertiary granites to the west.

The results of this work provide constraints on the kinematics of continental collision and on tectonic models for the evolution of the eastern Himalaya. However, it also poses new questions relating to the timing and tectonic relationship of the two vast bodies of granite in northern Bhutan.

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Anisotropy of Fracture Density and Connectivity Along and Across a Fault Zone and Its Effects on Fluid Transmissibility – Case Study from the Gubbio Fault

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Fault zones can be characterized by the anisotropy of fracture density and connectivity along three directions. Perpendicular to the fault plane different fault zone domains (fault core (FC), damage zone (DZ), protolith) can develop. Parallel with the fault plane, from the tip to the centre along strike the displacement of the fault increases, and the amount of damage changes. Parallel with the fault plane, along dip as the fault cuts through different rocks the lithological control on the damage is shown. The anisotropy of a fault zone along these three directions can strongly influence the fluid transmissibility of the fault.

In order to characterize and quantify the distribution of fracture patterns along and across a large displacement normal fault in carbonates, we studied the Gubbio fault (GF), in the Northern Apennines. The GF has a displacement of up to 3 km, and it crosscutts the Jurassic-Oligocene Carbonatic Multilayer (CM). The fault zone of the GF is exposed in fault orthogonal outcrops along strike, which display different formations of the CM that has different marl contents. Quantitative structural data was collected using 1D (structural transects), 2D (image analysis), and 3D (LiDAR) methods across a range of scales. The results of these analyses were integrated with field observations in order to produce and integrated model of fluid transmissibility.

Field observations and quantitative analyses show that the FC contains several 4-5 m wide domains, some made of low permeability marl rich fault rocks, while others of more brecciated carbonates with intense veining, and higher permeability. All domains are separated by well-developed slip surfaces crosscutting every other feature, and associated low permeability ultra-fine-grained cataclasites. In comparison, the DZ is over 200 m wide, both at the centre and at the tip of the fault. It is characterized by intense fracturing and subsidiary faults. Both types of features are dominantly parallel with the GF. Based on quantitative analyses, precipitated calcite in the fractures is 3 times more common at the center than at the tip of the GF. Fracture density is 8-10 times, connectivity is 12-14 times higher close to the FC than in the protolith. Connectivity values start to rise from their background level closer to the FC than density values. The more marl rich units show high microfracture density, but calcite precipitation in these fracture planes is rare.

Our data suggests that fluid transmissibility is anisotropic in the fault zone. In the brecciated domains of the FC fluids can flow both along strike and dip; however the low permeability domains and the ultra-fine-grained cataclasites at the slip surfaces behave as barriers. In the less marl rich units of the DZ fluid flow can occur both along strike and dip in the small fractures and also in the subsidiary faults. Fault parallel fluid transmissibility is decreasing from the FC-DZ boundary to the protolith and from the center to the tip of the fault. In the more marly units of the DZ fluid flow is only favored in the subsidiary faults acting as fracture corridors crosscutting these units and linking the more permeable carbonates. Fault orthogonal fluid flow in the DZ is only favored by the few fault orthogonal fractures and subsidiary faults, while the precipitated calcite in the fault parallel fractures and faults can act as barriers.

Carbonate Hosted Normal Faults in Malta: Variations in Deformation in Distinct Lithofacies

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Fault related deformation, and the scaling of such damage, has often been presented in simple architectural models (e.g. Caine et al., 1996). Measured fault damage is rarely straightforward, and can be influenced by lithological variations in the wall rocks. Faulting and fault related damage in carbonates are difficult to model and predict, as carbonates are inherently heterogeneous. Each distinct carbonate facies is likely to damage differently and experience different deformation mechanisms.

This talk presents preliminary results from an ongoing field and laboratory study using well exposed normal faults on Malta, with displacements ranging from ~20 cm up to ~95 m. The deformation surrounding faults in two main lithofacies – mud- and grain-dominated carbonates – has been examined and quantified. The data have been used to evaluate the main deformation mechanisms observed in the two carbonate facies and inferences made about their differing responses to stress. In addition, these differences in deformation mechanisms change the scaling relationships of the fault zones. Mud-dominated carbonates show a plastic response in fault cores destroying any pre-existing fabrics; while in the damage zone the original fabric remains and contains large, well spaced fractures. Grain-dominated carbonates show a high degree of cataclasis and dissolution in the fault core, but with more localised deformation within the damage zones, with clast-confined Hertzian fracturing rather than large through-going fractures. This suggests different scaling relationships for faults within these two facies, as well as associated variations in petrophysical properties across and along the fault surfaces. Our preliminary data suggest that faults in grain-dominated facies have thicker cores and thinner damage zones compared to those in mud-dominated facies, which have thinner cores and thicker damage zones.

Core and shale smear characterization along extensional faults in late pre-rift carbonates (Suez Rift, Egypt): Implications for fluid flow

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The distribution, composition and flow-properties of fault core and shale smears along faults in carbonate reservoirs is less well understood compared to faults in siliciclastic rocks. This study uses field data to characterize and quantify fault zone properties that are critical for understanding structural heterogeneity in carbonate reservoirs. We focus on (1) variability and co-dependence of displacement, shale smear potential, fault thickness, -composition and -geometry; (2) the effect of shale smearing on fault (core) deformation; and (3) implications for fluid flow in fault zones. The study area is located on the eastern flank of the Oligo-Miocene Suez Rift and features large extensional fault arrays affecting fine grained carbonates of late Cretaceous to Eocene age. The current study is based on structural data from two of these faults (3-4 km length; 0 to 500 m displacement). Our results show variations in the fault core geometry and composition along the faults; thickness ranges from 2 to 5 m. Compositionally, the fault cores are comprised of carbonate breccias, shale smear, secondary calcite and gypsum cement and host rock lenses. There is also a significant variation in the thickness of shale smear where present (up to 4 m thickness recorded). Investigation of the variability of the said fault parameters indicates that the properties of fault core and inner damage zone are affected by the presence or absence of shale smear. Shale smear introduces a weak mechanical layer in the fault, acting as a lubricant or cushion during slip. This appears to control the structural style and geometry of the fault core. In turn, both shale smear in its own right as well as fault core properties control the effect of any fault on fluid flow. Thus, the present study contributes with new knowledge relevant for fault seal analysis in subsurface carbonate reservoirs.

The effect of fault core composition and geometry on the permeability structure of faults in carbonate reservoirs

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Characterization and quantification of fault properties in outcrops is critical to improve forecasting and modelling of structural reservoir heterogeneity in sub-surface carbonate reservoirs. Key parameters for fault characterization include fault core thickness, damage zone width, composition, fracture frequencies, geometry and displacement. In this study we focus on fault core parameters in natural exposures of faults in late Cretaceous to Eocene carbonates in the Western Sinai Peninsula, Egypt. This area, which comprises the eastern flank of the Oligocene-Miocene Suez Rift, offers great exposures of extensional faults in fine-grained carbonates having undergone minor burial only. We base the study on data collection from 80 faults of displacement varying from 0.04 to 350 m. Our analyses indicate that the fault cores are composed of elements of carbonate breccia, shale smear, clay gouge and secondary calcite veins. Secondary calcite veins is most common in smaller faults (displacement <1m) and less so in intermediate (1-10 m displacement) and larger faults (10-350 m displacement). Carbonate breccias content exhibits a strongly positive correlation with displacement, whereas shale smear is most well developed in faults of intermediate displacement (1-10 m displacement) due to the shale smear potential being exceeded for the largest faults. Fault core architectures are highly affected by the mechanisms of interlinking fault segments and influence of mechanical contrasting layers. These variations are reflected in the considerable variability of fault core thicknesses, and the generally poor correlation between thickness (T) and displacement (D). The T/D data are scattered over three orders of magnitude, following a power law with exponent of 0.6. This indicates that thickness increase as a function of displacement is higher for small and intermediate faults (0-10 m displacement) than for large faults (10-350 m displacement), contrary to previous studies of thickness-displacement relations. The results of the present study have implications for the permeability structure of faults in carbonate reservoirs. Whereas small faults bear evidence for increased fluid circulation (secondary calcite veins) in the core, breccia and shale smear development in the cores of intermediate and larger faults are capable of significantly reducing fluid flow. We thus conclude that whereas the cores of small faults increase permeability, the cores of larger faults have the potential to significantly decrease permeability.

Keynote lecture

Scaling of brittle failure in space and time: impact on the predictability of volcanoes and earthquakes

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The notion of scale-invariance is one of the central tenets of structural geology. Charles Lyell was the first to note 'self-similarity' in deformation structures in the Alps. His work provided E.M. Anderson with a rationale for extrapolating the results of small-scale deformation experiments in analogue materials to continental-scale faulting. Sadly the mechanical and hydraulic properties, notably the presence of dilatancy-related precursors to dynamic failure in the laboratory, have failed to extrapolate similarly linearly to field scales, resulting in the failure of the dilatancy-diffusion hypothesis as a physical basis for earthquake prediction. In science we often learn more from hypothesis failure than its validation, so here we consider some of the potential reasons. One might be that the diffusion component invoked in explaining the nature of some reported precursors had not been observed in the laboratory at the time the hypothesis was proposed. However, the process of dilatancy-diffusion has now been clearly validated in a laboratory setting, with clear precursors in acoustic emission signals that can be predicted from a fracture mechanics model involving the concept of effective stress. The dilatancy-diffusion process also provides a very good explanation for the observation of near-fault, post-seismic strain recovery, for example in satellite data after the Bam earthquake in Iran. With hindsight one clear problem is the lack of appreciation of retrospective sample bias in the hunt for precursors in noisy and often spatially-localised geophysical signals, but this does not of itself explain the general absence of reliable precursors. One underlying reason may be the issue of spatial scaling, with different boundary conditions, sample size to grain size ratios, and material complexity, as well as the validity or otherwise of the notion of a 'preparation zone' which would determine the size of the upcoming event. This notion has been challenged by recent seismological and geodetic evidence for rather localised nucleation, consistent with the notion that event size may be an emergent rather than a pre-determined property of an earthquake. Finally recent experiments have shown a systematic decrease in predictive power for acoustic emission precursors as strain rates are slowed down. We conclude by describing a series of new planned tests to plug the gap between timescales for laboratory, volcanic and earthquake nucleation processes, and discuss the implications for the ultimate predictability of dynamic failure in Earth materials.

Spatial characterization of deformation in high porosity sandstones: from outcrop data to fluid flow circulation

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Understanding the evolution of fault zone geometrical and hydromechanical properties during fault growth and network development is of major importance in fluid flow prediction in the crust. In porous rocks, faulting produces zones of deformation bands rather than planar fracture surfaces. Cataclastic deformation bands (CDBs) are mm-cm thick brittle shear zones that form through the combined effects of compaction and cataclasis.

Plans for CO_2 storage in porous sandstones must consider the role of deformation band-dominated faults in trapping or retarding the flow of CO_2. Most commonly CDBs show a reduction of porosity, associated with a reduction of permeability. This permeability decrease is largest for the most evolved and thick zones of CDBs. Conversely, slip planes can potentially have a higher permeability than the host rock. Therefore CDBs in sandstone reservoirs can potentially retard fluid flow circulation and act as barriers to fluids, whereas slip planes could be conduits for flow. Previous studies have examined the effect of connected deformation band systems on flow, but have not considered the effect of “open” slip planes. To predict the effect of such structures on fluid flow we must consider the 3D connectivity of the relatively low permeability CDBs and any high permeability slip planes. To characterise this connectivity we have chosen to undertake detailed mapping of structures affecting deformed sandstones in the United Kingdom (Isle of Arran), France (Provence) and USA (Utah).

Detailed maps allow us to identify potential fluid flow pathways through the mapped network, and to derive statistics to describe the density, tortuosity and connectivity of such pathways. For instance, the thickness of the low permeability CBDs is an important variable for retardation of flow, but this flow barrier may be compromised by a large number of through-going or cross-cutting high permeability slip surfaces. The field data collected by this method were used to derive variograms of key fault zone components (e.g. fault zone thickness, CDB width, number of cross-cutting slip surfaces) to characterise their variation along strike. These variograms can be used to generate numerical realisations of faults at depth with robust statistically-based fault zone properties that vary along strike. The choice of different lithologies, different tectonic events and different burial depths will allow this research to better constrain the relationship between the fault statistics we derive from a variety of field exposures and the properties of faults at depth.

Characterising Fracture Porosity Around Fault Zones

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Microfractures in fault damage zones comprise much of the porosity around faults. Pore fluid pressure changes in this damage zone porosity can alter the geomechanical risk for fault reactivation. Accurate predictions of fault stability in clastic reservoirs and their top seals are vital for the extraction of hydrocarbons, the injection of water into reservoirs and the storage of CO_2. Field and experimental evidence shows that damage zone porosity, in the form of microfractures is anisotropic and patterned (Anders and Wiltschko, 1994). Depending on the orientation of these crack patterns with respect to the principal stresses, this anisotropy may either increase or decrease the strength of the rock. This study aims to quantify spatial and directional variations of damage zone porosity and integrate this information into a new method for predicting fault reactivation.

Field data has been collected from two fault zones. The Clashach Fault (Moray) is a sub-seismic scale extensional fault that cuts through the Permian aeolian Hopeman Sandstone Formation. The damage zone is around 3 m wide, defined by intense fracturing. Macrofractures measured along a 50 m scanline show a rapid decrease in fracture intensity away from the fault plane in both hanging wall and footwall. The North Scapa Fault (Orkney) is a seismic scale extensional fault that juxtaposes lacustrine Middle ORS Stromness Flagstone Formation in the footwall against the younger fluvial Upper ORS Scapa Sandstone Formation in the hanging wall. Fracture intensities are very high in the hanging wall, and show a gradual decrease away from the fault plane. The damage zone is a 15 m wide zone without clear bedding lamination with a further 35 m of intense fracturing with visible cross bedding. Footwall fracture intensities are lower than in the hanging wall and decrease quickly from the fault plane. Damage zone samples were cored and thin sectioned at three orientations (x, y, z) to the fault plane. Initial results from petrophysical analysis indicate directional variations in porosity with respect to the fault plane and differences in permeability between hanging wall and footwall, and along fault strike. Evidence of preferential flow pathways or anisotropy of permeability has also been observed in both fault zones in the form of bitumen staining of damage fractures and variable cementation.

Thus detailed maps, cross sections and fracture scanlines across two fault zones reveal variations in the intensity and orientations of deformation both laterally and perpendicular to the fault planes. Quantitative analysis of petrophysical data has shown distinct variations in structural heterogeneity and anisotropy in rocks from different clastic environments. Such heterogeneity could act as high permeability pathways or barriers to flow, and may also influence the mechanical strength of the rock.

The formation of breached relay zone geometries from splay propagation.

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Faults commonly consist of arrays of en echelon segments. Displacement is transferred between a pair of adjacent segments by deformation of the intervening rock volume, or relay zone. In normal faults this deformation gives rise to bed rotations to form a relay ramp between segments. In most current models of relay zone evolution describe a progression of structure from an intact relay ramp, with ramp rotation increasing as displacement increases, through to the formation of a through-going fault when the relay ramp is bypassed, or breached, by the formation of a fault linking the initial segments. This evolution has been proposed from extensive studies of relay geometries at different displacements and is supported by the relatively much fewer studies of relay zone kinematics.

We present the results of detailed kinematic analyses carried out using displacement backstripping on a segmented fault array from South East Asia which demonstrate a more complex 3D evolution of segment boundaries than this simple model suggests. Our analyses show, not only that a relay ramp may be breached at one structural level and simultaneously intact at another, but also that ramp rotation can continue after the formation of a through-going fault. The data also show that an initial through-going fault bend can, with increasing displacement, develop a splay and a related intervening zone of high strain. This geometry arises when a relay bounding fault propagates to structural levels at which a fault bend has already been established. In this case fault and bed geometries very similar to that of a breached relay ramp can be reached by an alternative mechanism i.e. the ‘ramp’ and splay forms after a fault bend is established.

400,000 years of fault related and man-made leakage from an analogue for engineered geological storage of CO_2

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Abstract

Carbon capture and storage (CCS) is one of a portfolio of technologies that could prove critical to reducing anthropogenic greenhouse gas emissions[1]. A significant challenge to the successful deployment of CCS is the demonstration of safe geological storage. CO_2 could migrate from storage reservoirs through boreholes, poor cap rocks, or natural fractures to leak at the surface. Maintaining atmospheric conditions close to a low-emission projection with no CCS, i.e. to avoid delayed climate effects of leakage from geological storage sites, may require <1% leakage of injected CO_2 per thousand years[2]. To evaluate long-term site suitability over thousand year timescales and to optimise techniques for monitoring the fate of injected CO_2 it is crucial to investigate potential causes of leakage, constrain leakage magnitudes and determine the scale of impact at the surface. We investigate two fault compromised sites from the Colorado Plateau which provide natural analogues for failed engineered storage of CO_2. This area is especially relevant for North Sea comparisons as it has a similar Mesozoic stratigraphy and is undergoing uplift as result of glacial unloading. The presence of multiple active and fossilised carbonate spring deposits, known as travertine, in both locations shows that there is a different style of leakage in each site. In one site leakage has been restricted to the damage zone of the fault due to the presence of several low permeability layers in the overburden whilst in the other the presence of consecutive unconfined aquifer units in the stratigraphy allows for a more diffuse pattern of leakage at the surface. In both locations active deposits are associated with abandoned and poorly completed exploration wells.

We interpret the fluid flow history of each fault by using U-Th isotope dating on the travertine deposits. Our data show that leakage pathways have switched repeatedly over km-scale distances for over 400,000 years and that individual leakage pathways were active for up to 11,000 years. Coupling age data with measurement of travertine volume we calculate magnitudes and rates of CO_2 release and compare focussed leakage from fault zones, diffuse leakage through unconfined aquifer units and leakage from boreholes. We find that the magnitude of leakage from fault focused systems is up to five times greater than diffuse leakage through high permeability units. The leakage rates from boreholes are up to 13 times that from the fault focused natural springs, demonstrating that well failure provides by far the greatest risk for future CO_2 storage sites.

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Climate driven CO_2-degassing from intracrustal faults

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Understanding the performance of faults, as either barriers or conduits to the flow of CO_2, is crucial for predicting the long-term integrity of geological CO_2 storage sites. Of specific concern are the relative importance of geochemical reactions on the sealing behaviour of the fault, and the impact of seismicity and stress regime on fault stability. This paper presents a 135,000 year paleorecord of CO_2-leakage from a CO_2-degassing fault in Utah. U-Th dated carbonate veins[1], deposited from CO_2-charged fluids[2], are examined. Temporal changes in the isotopic ($^{13}C/^{12}C$, $^{18}O/^{16}O$ & $^{87}Sr/^{86}Sr$) and trace element (Ba/Ca & Sr/Ca) composition of the veins record four major pulses of CO_2 injection into the local groundwater system. As a consequence surface CO_2-leakage rates increase by several orders of magnitude. Each pulse occurs ~100-2000 years after the onset of major local climatic warming, at the transition from glacial to interglacial conditions. The removal of large crustal loads during glacial-interglacial transitions, including emptying of Lake Bonneville and retreat of glaciers in the Uinta Mountains, has been shown to have a marked impact on slip accumulation and seismic activity on regional faults (e.g. Ref 3). Locally, the absence of evidence for surface rupturing earthquakes, suggests that CO_2-leakage was not triggered by large slip events. Geochemical and structural analysis suggests that the fault leaks as a result of fracture opening, driven by locally elevated pore pressure resulting from: i) an increase in local compressive stresses due to crustal unloading; ii) an increase in groundwater recharge and artesian conditions at glacial-interglacial boundaries and; iii) the intermittent presence of a buoyant CO_2-gas cap in the fault footwall. Globally, many large fault zones show a marked increase in CO_2-flux during periods of seismicity (see review in Ref 4). An increase in CO_2-degassing from regional faults, following glacial unloading, would increase the solid earth CO_2-degassing budget, creating a warming feedback, the significance of which remains to be tested.

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Improving side seal predictions on faults by integrating geometric and property uncertainty: Examples from well constrained Gulf of Mexico fields

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Detailed outcrop studies indicate that fine scale fault architectures are key to the understanding of fault zone properties and cross-fault fluid distributions. The correct application of lithological and fault zone properties to sub-seismic-scale deformation models are crucial to understanding the importance of fault seal characteristics and fluid behaviour.

In this contribution we demonstrate the importance of integrating geometric and property uncertainty in characterising fault juxtaposition patterns and fluid sealing properties to explain observed cross-fault fluid contact distributions.

An accurate prediction of fault/side seals is increasingly important in efficient exploration and extraction of the remaining limited natural energy resources. Side seals are also becoming increasingly important when considering carbon capture and sub-surface storage.

Geometric models of several Gulf of Mexico reservoirs have been constructed and combined with the stratigraphic distributions defined from wells. These models have then been combined with the known fluid distributions. These base case models have then been integrated and compared in terms of both geometries and properties. The resulting side seal predictions have then been tested against the known fluid contact distributions. This approach allows the range in viable structural configurations to be highlighted.

The detailed geometries and properties that control sealing are often well below the imaging and sampling resolution available to define the form of the structure (e.g. seismic and well data). In this example we show how integrating geometric and property uncertainty can help define the likely range in viable properties and geometries. This data should act as a guide when considering whether and how much uncertainty should be integrated into the modeling process when trying to estimate side seal and bulk fluid behaviour.

Damage zone/fault core; an unhelpful view of fault zone structure?

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The standard outcrop description of fault zones currently in vogue is a high strain fault core containing fault rock surrounded by a low strain halo termed a damage zone. These terms began to gain prominence about 15 years ago largely because they provided a convenient description of faults in high porosity sandstones where fault zones are frequently flanked by a wide zone of deformation bands. The terminology has subsequently become the standard description of faults in most outcrop studies, and is increasingly used in studies of fault zone evolution based on the assumption that core and damage zone have some generic or mechanistic significance. That this is not the case is highlighted by studies describing the many and varied processes which lead to the formation of structures included under the term ‘damage’; these include normal drag, fault segmentation and relay ramps. Similarly, recent articles have recognised ‘multi-cored’ faults suggesting that they are generically different to ‘single-cored’ faults despite the routine observation that a fault may branch and rejoin.

While the damage zone/fault core description may be convenient for 1D or effectively 1D samples through faults (core or small outcrops of large faults), usually in circumstances where displacements are not defined, it is clear when extensive outcrop or seismic datasets are available that this description does not capture the main features of fault zones. For example, segmentation is a fundamental feature of faults and linkage between segments is arguably the main process in fault zone evolution. However fault segmentation and the associated spatial variation in fault displacement is not incorporated in core/damage zone descriptions. Attempts to quantify fault zone structure in terms of merely core and damage zone dimensions are therefore not relevant to the study of segment linkage or the impact of segmentation on fluid flow within or across fault zones

Outcrop studies can best contribute towards an understanding of fault zones if they are set in the context of an appropriate 3D appreciation of faults, including quantitative definition of internal displacements and strain. Fault terminology should be guided by those datasets where 3D fault zone structure can be deciphered rather than by what is convenient in outcrops where it cannot. We suggest that the damage zone/fault core description promotes not only a simplified view of faults, but also a misleading one which is an obstacle to understanding them.

Damage zone evolution and permeability structure of segmented normal faults

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Normal fault systems almost invariably comprise segments of different orientations that jog, branch, bifurcate, or link. It is now well understood that these map view expressions form as normal fault systems evolve as fault segments localize, grow, link and amalgamate to form longer, continuous faults. Previous work has shown that areas of fault interaction and linkage are associated with considerable structural complexity compared to isolated single fault segments. This contribution presents case studies from siliciclastic (Jurassic, Colorado Plateau, Utah) and carbonate (Eocene, Suez Rift, Egypt) systems, and aims to (1) elucidate the role of fault linkage zones (relay zones) in controlling damage zone architecture and properties in order to (2) better understand the permeability structure of segmented normal faults in subsurface reservoirs.

Our analysis shows that in carbonate rocks, damage zones associated with fault linkage produce significantly elevated fracture frequencies and a wider range of fracture orientations as compared to isolated fault segment. These localized fracture systems lead to a significant increase in cross-fault and along-fault permeability in the linkage zones. In siliciclastic rocks, a similar increase in structure frequency and orientation is seen in linking damage zones, but the structures produced are chiefly low-permeable deformation bands. Reservoir modeling and fluid flow simulation show that the deformation bands decrease the total effective permeability of the linking damage zone. Our results are compared to previous finds in the literature, and a synthesis of damage zone evolution and permeability structure of segmented normal faults in siliciclastic and carbonate systems is presented: (1) Fluid flow in relay zones is controlled by reservoir bed connectivity (soft linked relay ramps) and the permeability structure of the damage zone (soft-linked and hard-linked relay zones). (2) Along segmented normal faults in carbonate rocks with low initial porosity and permeability, fault linkage zones represent locations of progressively increased *cross-fault* effective permeability through the stages of relay growth and breaching. (3) In siliciclastic rocks, low-permeable deformation bands reduce the effective permeability of soft-linked relay beds, which nevertheless provide a conduit across otherwise potentially sealing faults. In the hard-linked stage in siliciclastic rocks, the combination of breached reservoir bed connectivity and low-permeable damage zone causes linkage zones to represent *cross-fault* permeability minima along segmented normal faults. (4) Fault linkage zones in both carbonate and siliciclastic rocks are associated with increased (vertical) *along-fault* effective permeability in all stages of relay growth and breaching.

Multiphase Fault Evolution in a Rotational Margin Setting: Offshore Sirte Basin, Libya

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The Sirte embayment, offshore Libya is a structurally complex Mesozoic – Cenozoic extension of the Sirte basin on the northern margin of Africa. Despite the Sirte basin being ranked 15th in the list of producing oil provinces by the USGS, the structure of the offshore part of the basin remains poorly constrained with few studies carried out there in comparison to the surrounding onshore and offshore areas. This study aims to redress this imbalance by providing a fault model and evolution hypothesis constrained by recently available 2-d and 3-d seismic data.

Multiple phases of rifting can be observed in the offshore area affecting a number of different horizons from basement through to Miocene with major faulting episodes during the Aptian – Albian, Upper Cretaceous, mid Eocene and Oligocene. Pre-Hercynian basement structures have a dominant role in the positioning of later faults and the orientation of basement faults with respect to strain direction influence the type of faulting observed. Several structural regimes exert an influence on the evolution of the Sirt embayment with well documented occurrences of NW-SE trending horst and graben blocks to the South, dextral shear dominated pull apart basin to the West, Ionian abyssal plane to the North and E-W trending faults showing inversion tectonics to the East.

The proximity to the surounding regimes causes variations in fault patterns and evolution across the basin with the southern most offshore area showing similar fault patterns to the onshore Sirte Basin with NW-SE oriented basement structural highs and lows extending from the onshore into the near offshore. These structures terminate close to the present day coastline, and give way to a dextral strike-slip regime oriented E-W as the Sabratah-Cyrenaica basement fault zone passes through the Sirt embayment. The central part of the offshore basin is dominated by a deep fault bounded trough extending from the SW and is the offshore extension of the onshore Ajdabiah trough. The NE part of the offshore area also shows a general NW – SE trend in fault orientations, but the influence of compression during the Santonian and mid Eocene has caused inversion on some faults and basement blocks. To the North another basement structural high is encountered trending WNW-ESE before the seabed drops rapidly away to the Ionian abyssal plain, and the influence of Jurassic oceanic crust production can be seen as Jurassic half grabens on both sides of the structural high.

During the timing of the rifting from Jurassic to Miocene, the margin has rotated by a significant amount and fault orientations do not today necessarily appear in the same orientation in which they formed. By rotating the orientations back to the time they formed, paleo-stress fields have been inferred and checked against published data.

Controls on the Lateral Variation in Structural Style Along an Evaporite-Influenced Normal Fault Array, Halten Terrace, Offshore Mid-Norway

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The Halten Terrace is underlain by a Triassic evaporitic package, resulting in decoupling of normal fault systems during Mesozoic crustal extension. The fault systems that bound the eastern margin of the Halten Terrace show considerable along-strike variation in structural style. Mapping of faults and key seismic horizons on 3D seismic data, analysis of throw variations along faults, and seismic attribute analysis to identify likely evaporite facies, allow us to constrain the factors that influence the evolution of rift-related structural styles in this evaporite-influenced setting.

Four structural domains are identified along the eastern margin of the Halten Terrace, from north to south: i) dominantly thick-skinned normal faults that affect both sub-salt basement and supra-salt cover, ii) basement-restricted normal faults associated with partially decoupled, fault-propagation folds, iii) dominantly thick-skinned, relatively distributed normal faults, and iv) dominantly thick-skinned, relatively localised normal faults. An abrupt change in structural style in the north of the study area is controlled by a fault domain boundary associated with a basement-involved, thick-skinned, NE-striking fault. Measurements of summed throw and estimated strain across the fault system show that the amount of throw and strain accommodated by the basin margin fault system increase towards the south, corresponding to a change to more localised faulting. The thickness of the evaporite package varies across the study area, with thickened areas occurring in the hangingwall areas of NE-striking, basement-involved, fault systems. However, variations in salt thickness do not correspond spatially to variations in structural style. Wireline logs from wells that penetrate the evaporite package, and volume attribute analysis of 3D seismic data, suggest marked facies variations in the upper of the two evaporite units. For example, a change in seismic facies from high-amplitude, low variance to low-amplitude, high variance corresponds to a change from dominantly decoupled to dominantly thick-skinned faulting. We conclude that the sub-evaporite fault template, the amount of strain accommodated across the fault system, and facies variations in the evaporite influence structural style, but variations in evaporite thickness are not large enough to influence style.

The growth and linkage of salt-influenced extensional faults: Egersund Basin, Norwegian North Sea

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The structural style and evolution of normal fault systems above thick, mobile salt layers is less well understood compared to the normal faults developed in rifts where strong variations in mechanical stratigraphy are absent. This study uses 3D seismic reflection and well data from the Egersund Basin, Norwegian North Sea, to document the structural style and growth history of a salt-related normal faults array. To evaluate the evolution and morphology of the salt-influenced faults we apply the following methods: 1) 3D mapping of faults and age-constrained growth strata, 2) geometric and kinematic classification of the fault segments, and 3) three-dimensional mapping of displacement distributions on the fault surfaces. Our analysis indicates that several of the faults exhibit linkage geometries that differ from segmented faults in basins that lack salt. In the northern part of the basin, the growth of a low-relief salt pillow led to the development of a thin-skinned normal fault array, c. 16 km long and approximately 6 km wide, where the general dip directions of the faults are either northwest or southeast. Throw generally increases northward along the fault array from 40-60 ms, in the south, to a maximum of c. 140 ms in the north. Present-day throw distributions suggest both lateral and dip growth and linkage. Furthermore, the intricate, but systematic style of displacement and growth, suggest a staged evolution of (1) initial syn-sedimentary fault growth and (2) subsequent reactivation and blind propagation of some structures. Growth strata indicate syn-sedimentary faulting at the transition between Skagerak and Bryne formations (Late Triassic - Early Jurassic), which is contemporaneous with growth of a salt pillow to the west. The reactivation of the faults may either be caused by later salt mobilization or a later tectonic event. Three-dimensional seismic data has provided important insights into the development of salt-influenced normal fault arrays; in particular we will highlight the lateral growth and linkage and the importance of dip linkage and blind fault reactivation.

Fault evolution during polyphase extension: Horda Platform, North Sea

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Not all petroleum systems in rifts have been produced by a simple history of single phase faulting followed by thermal subsidence. Many hydro-carbon bearing rift basins have experienced multiple phases of extension, and the superimposition of normal faults has resulted in complicated basin and trap geometries (e.g. South Atlantic, North Sea). Such a complex rift history causes problems in predicting the distribution and quality of reservoirs.

We investigate the effect of multiple rift phases on the evolution of normal faults in the Horda Platform area of the North Sea, including those that bound the Troll field. Pre-rift basement and deep structures are imaged by 2D seismic reflection data and shallower structural and stratigraphic features within the overburden are imaged by high-quality 3D seismic data. The lateral and vertical distribution of fault throw is assessed and a fault evolution model is presented for the eastern margin of the rift basin.

Rifting in the Horda Platform started during the Permian-Triassic (PT) and involved initiation of originally isolated, W-dipping normal fault segments, which eventually linked to form ~100 km long fault systems that bound three half-graben and terminate to the north against a granite-cored structural high. These PT faults were not reactivated during the Middle Jurassic rift phase, despite the initiation of normal faulting in the nearby Viking Graben. During the Middle Jurassic, however, a series of N-S striking faults began to develop directly to the north of the PT fault population, and deformed the previously un-faulted granitic basement. These faults terminate to the south near the northern tips of the PT faults, in the location of a suspected crustal shear-zone (the Nordfjord-Sogn detachment). Reactivation of PT faults did eventually occur in the Early Cretaceous, at a time when subsidence is commonly thought to have been driven by thermal relaxation.

The style of faulting in the Horda Platform appears to be controlled by an older crustal fabric. Large PT faults developed south of a suspected crustal shear zone, and show limited Middle Jurassic reactivation. A large granitic footwall basement high may have supplied sediments southward to pre-Middle Jurassic reservoirs within these tilted fault blocks. New faults initiated during the Middle Jurassic to the north of the shear zone and have experienced significantly greater Early Cretaceous reactivation than the larger PT faults.

Keynote lecture

The role of structural geology in the past, present and future development of the UK Continental Shelf

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Structural geology in the UKCS oil and gas industry has evolved greatly in the last few decades - from simple, hand-drawn models borrowing extensively from onshore experience elsewhere, through crustal-scale concepts constrained by geophysical observations and mathematical modelling, to process-based approaches addressing topics such as reservoir compaction or fault seal and reactivation. Collaboration and cross-fertilisation between academia and industry has been a common theme, with released commercial data triggering new scientific concepts which were taken up by operators keen to acquire a competitive 'edge'. Calibrations developed in the UKCS and the adjacent Norwegian shelf have become embedded in the global literature. What scientific and technological challenges and opportunities can we expect in the next decade in this data-rich, mature basin, and where might the next generation of academic-industry collaborations lead?

Landscape Evolution of Madagascar and Africa through the Cenozoic Era

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It is generally accepted that the surface topography of Africa is a manifestation of sub-lithospheric mantle convective circulation. Here, we present an inverse method whereby longitudinal river profiles are used to extract quantitative estimates of spatial and temporal variations in the rate of tectonic uplift. Surface processes can provide an important window into transient convective circulation in the sub-lithospheric mantle. River profiles act as 'tectonic tape recorders': we assume the generation of broad, convex-upward knickzones to represent the effect of tectonic uplift shifting the river system into a state of disequilibrium. Profiles evolve through time primarily via the headward retreat of these knickzones. We use a conjugate gradient algorithm to minimise the misfit between observed river profiles – derived from a regional Digital Elevation Model (DEM) – and calculated profiles obtained by varying the uplift rate history. We jointly invert a total of 88 Malagasy and 570 African river profiles to obtain a history of the cumulative tectonic uplift through geological time. We show that Africa has undergone two phases of rapid uplift: first in Eocene times; secondly, since 10 Ma. While the first gave rise to broad, long wavelength topography, the second led to more localised domal swells of high relief. We propose the existence of two wavelengths of dynamic support, reflecting a change in the style of convection in the upper mantle since 50 Ma. Our results correlate strongly with independent geological estimates of uplift across Africa and Madagascar, while our calculated surface folloing 50 Myr of uplift corresponds closely to a surface fit across present-day drainage divides. Finally we calculate the solid sediment flux delivered to major African deltas as a function of time. This onshore record provides an important indirect constraint on the history of vertical motions at the surface, and agrees well with the offshore flux record, obtained from mapping the thickness of chronostratigraphic sediment packages at the deltas.

Modelling in-plane compression and thermal anomalies: Application to the post-rift evolution of the Rockall Trough

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The Rockall Trough is one of the largest of the relatively unexplored basins that form the North-East Atlantic passive margin, and many aspects regarding its evolution remain unresolved. Throughout the Rockall Trough there are significant departures from classical post-rift thermal subsidence models. These include the regional Palaeogene uplift, which resulted from the Icelandic Hotspot and associated thermal anomalies and during the Late Eocene a major deepening event across the Rockall Trough. Possible explanations for this event include compressional related buckling of the lithosphere or the loss of thermal support associated with the Icelandic Plume.

The main aim of this study is to apply numerical, lithosphere-scale models to the Rockall Trough in order to gain insights into the mechanisms responsible for deepening and uplift events as well as other observed departures from classical rift and thermal subsidence models. These models are used to test different hypotheses regarding the timing and nature of extensional and compressional events and the influence of thermal anomalies. The thermal anomaly resulting from the Icelandic Hotspot has been modelled to assess the impact it may have had on the evolution of the post-rift subsidence in the Rockall Trough.

Numerical modelling results show that compression during the Eocene can produce the rapid acceleration of subsidence observed in parts of the Rockall Trough. However, the magnitude of compressional related subsidence depends on the existing flexural deflection prior to compression. Consequently the interplay between elastic thickness (Te), the crustal necking depth, the amount of material removed from the crust through both erosion and crustal thinning, and basin infill is crucial to accurately model the effects of compression on basin development. In this study synthetic gravity profiles of the modelled cross-sections are compared with regional gravity data in order to validate the results produced.

Three-dimensional modelling of structural, thermal and isostatic processes is currently being developed in order to fully understand the evolution of the Rockall Trough. Initial model results show that the proximity to the Icelandic Hotspot, major terrain boundaries, and Caledonian basement structures, play a vital role in the evolution of the Rockall trough, and may explain the differences observed between the northern and southern sub-basins.

Vertical stress magnitudes in the Northern Niger Delta Basin, Nigeria: The constraining factor for overpressure prediction

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The elusiveness of complete stress histories in Cenozoic deltaic basins is of paramount concern to both researchers and industries. It is particularly indispensable in prolific basins such as Niger Delta Basin, Nigeria. There are few stress signatures on rocks to link them to their tectonic frameworks. In the Miocene, the eastern part of the delta was ripped several times by uplift and erosion. The forces that induced gravitational settling of growth faults and shale tectonism could not be solely deemed to account for the present stress magnitude in the basin. In the Normal fault regime, which is the dominant stress regime in the onshore part of the basin, the vertical or overburden stress (σ_V) is the maximum principal stress. Vertical stress magnitude is a critical determinant for well bore stability, casing design, completion and constraining overpressure magnitudes in shales tending towards the fracture gradient. An appropriate degree of fit is achieved by formatting the density logs from 64 wells in the basin and removing spurious readings due to well bore conditions before training them to estimate average density from the surface to the top of logs. The final density values were translated to vertical stress using Jaeger and Cook (1972) method. The results show a proportionate increase in σ_V gradients with depths. At 2 km (6,562 ft) depth, σ_V gradients vary from 19.38 MPa/km (0.86 psi/ft) to 23.04 Mpa/km (1.02 psi/ft); at 3 km (9,843 ft) σ_V gradients vary from 21.80 Mpa/km (0.96 psi/ft) to 24.54 MPa/km (1.08 psi/ft); at 4 km (13,123 ft) depth σ_V gradients vary from 23.68 Mpa/km (1.05 psi/ft) to 25.23 MPa/km (1.12 psi/ft). The variations in the vertical stress gradients across the basin are attributed to differential formation bulk densities from 1.98 to 2.57 g/cm^3. In the hydrostatic zone, the result of pressure prediction using the Eaton (1972) method is consistent with an increase in pressure due to an increase in vertical stress but in the overpressured area, the vertical stress decreases with a pressure increases. Two wells were removed from the study due to abnormal pressure values at intermediate and deep levels attributed to gas injections in nearby production wells. There are variations in the top of overpressure in depth versus vertical stress and depth versus mud weight in five wells which are ascribed to the use of underbalanced mud weights in adjacent shales. The basin wide vertical stress anisotropy is a direct consequence of the depositional rate of the classic sequences and disequilibrium compaction which caused high magnitude overpressure and stress anomalies at depth.

Structural styles of the Nankai Accretionary Prism, off SW Japan: comparisons of core, LWD and seismic data

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The purpose of IODP expeditions at Nankai Trough, off SW Japan, is to reach to the seismogenic zone of the subducting Philippine Sea Plate. During the first stage of this NanTroSEIZE project, drilling was conducted at six sites transecting the accretionary wedge in 2007-2008. By using the cores and logging-while-drilling (LWD) data acquired during the expeditions, their structural data were compared with 3D seismic dataset.

Among various LWD data, we used borehole resistivity images to extract structural data, e.g. bedding planes, fracture surfaces and borehole breakouts, to interpret structural styles of the area. Core structural data were identified by Expedition 315 and 316. Three-dimentional structural surfaces were also interpreted in the 3D seismic data around the wells, and the dip and azimuth were determined based on the resolution of the dataset.

The structural dataset from three different scales of observation can be correlated, but differences that cannot be ignored also exist. Such differences may be caused by differences in resolution/accuracy of the dataset, in principles used to acquire the data, and in real structural styles at different scales. This suggests that care must be taken to understand the resolution and principles of acquisition of each dataset where structural dataset of different types and scales are combined.

Reference

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The deformation history of syn-orogenic foredeep basins as a clue for orogenic dynamics : a case from SW Tuscany, Northern Apennines, Italy

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Foredeep basins flanking mountain belts provide a clue for the interpretation of orogenic dynamics. When studying recent or active mountain belts, whose history is still well preserved in the foredeep sedimentary record, the kinematics of folding and thrust emplacement may be effectively unravelled through the analysis of deformation fabrics and their overprinting relationships observed within syn-orogenic deposits.

The Northern Apennines of Italy represent a classical ground for the study of orogenic processes through investigation of associated foredeep basins. Much information has been inferred by observations of stratigraphic and sedimentological features of syn-orogenic deposits, yet with relatively little attention to the superimposed deformation structures.

The Upper Oligocene Macigno Formation that crops out in the coastal section of SW Tuscany represents the sedimentary fill of a foredeep basin developed during the collisional stages that led to the construction of the Apennine mountain belt. The stratigraphic sequence consists of alternating sandstones and siltstones, that are affected by Km-scale contractional structures, namely SW-dipping thrusts and related NE-verging folds. An original field survey carried out at the 1:5000 scale along a superb coastal exposure, integrated with analysis of mesoscopic fabrics and of their overprinting relationships, makes it possible to unravel a complex deformation history. Three main deformation stages are recognised: i) top-to-the-foreland shearing; ii) folding and iii) thusting. Individual stages are correlated with the main tectonic phases related to the progresive deformation history of the Macigno Fm. basin and to incorporation of its sedimentary fill within the evolving Apennine orogenic system.

The kinematic history inferred from deformation fabrics and their overprinting relationships within Macigno Fm. deposits in SW Tuscany shows remarkable analogies with the structural evolution of foredeep sediments from other fold-and-thrust belts, yet with little deviations. These provide original information on the modes of accretion of foredeep deposits within evolving orogenic belts, thus contributing to an enhanced understanding of orogenic dynamics during mountain building.

Keynote lecture

A Balancing Act – a thirty year perspective

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Despite the fact we have been balancing sections now for something like 100 years and with the digital age balancing has evolved considerably and we have seen the approach become central to many high value industry projects.

With ever increasing demands for resources (hydrocarbons, minerals, water), and the need, and indeed the pressure, to find and produce these at the lowest "stakeholder" cost we need to make better geological interpretations. This includes not just the static present day geological framework but to interpret and understand in a constrained and balanced way the entire evolutionary process of the structure. The kinematic evolution allows us to make predictions of sediment distribution, framework compartmentalisation and fracturing and the fluid system that carries the hydrocarbons or minerals. This predictive capacity adds real commercial and societal advantage in managing resource risk and security and in guiding sequestration of waste materials.

The procedure is still not routine practice nor, indeed, seen by many professions as essential best practice. Routinely published interpretations don't balance either in classic 2d or more importantly in 3d. Bond has shown what we all suspected, that without interpreting with a consideration of balance the uncertainty in the interpretation and the prevalence of geologically in valid interpretations increase dramatically.

The big question is why as a profession we have failed to make this approach a "must do" best practice and what we need to do to change this situation. Clearly this involves the whole professional journey from early training and engagement with understanding process through to continuing professional development throughout our careers. In particular the challenge is to make balancing easier, and more accessible through use of appropriate technologies and support.

Using high resolution multibeam bathymetry to analyse a strike-slip fault network

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A strike-slip fault network was mapped using high resolution multibeam bathymetry data offshore from Hartland Point, north Devon. The data were collected as part of the UK Civil Hydrography programme and were imported into ArcGIS where a geo-referenced 3D image with a pixel resolution of 0.5 m was created. The data were processed to produce slope, aspect and hillshade images which accentuated bedding and fault traces. The degree of slope, combined with measurement of the strike of identified bedding planes, allowed determination of the strike and dip of bedding. Each fault trace was digitized along with cut-offs of marker beds allowing the calculation of multiple, lateral separations along fault traces. The fault traces were then segmented at each measured offset point and an average displacement determined for each fault segment.

The multibeam bathymetry reveals a submerged platform of bedrock extending ~2.5 km from the shore line. This provides a much more extensive area of faulting to be mapped (~16 km^2), than that exposed at low tide on wave-cut platforms. The high quality and shallow water coverage of the multibeam data allowed direct correlation and mapping of bedding and faults onto air photography of onshore wave-cut platforms. Fold structures are visible from the imagery and marker beds can be traced around fold hinges. Stereographic projections of offshore bedding measurements show that the folds trend approximately E-W related to N-S compression and the geometry agrees closely with that mapped onshore. Mapping indicates two distinct fault sets: NW-trending right-lateral faults and NE-trending left-lateral faults. The faults cut and offset both layering and fold axial traces, laterally moving limbs and hinge lines of folds in the same direction. This combined with onshore 3D structural data indicates the faults are strike-slip and post-date folding.

The ability to use multibeam bathymetry data to extensively and uniformly map a fault network opens up many opportunities to further the analysis of fault networks by studying real examples that are not exposure limited. Furthermore, the measurement of displacements along each fault trace allow other attributes (e.g. strain, fault size distributions, connectivity, etc.) to be analysed. Our results show the distribution of strain and variation in topology with scale. We conclude that although strain is localized onto large fault segments with >=10m displacement, 14% of the strain is still accommodated on small fault segments with <10m displacement. Furthermore, the connectivity is very dependant on the small fault segments emphasizing the importance of resolution when estimating/investigating the strain and connectivity of fault networks.

Flexural basin reworked by salt-related strike-slip termination pull-apart structures: the Adony Basin

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The structural analysis of recently gathered 3D seismics in the Adony Basin and adjacent 2D lines has been performed. The basin lies to the south of Budapest, the capital of Hungary. Being in the central part of the Mid-Hungarian Shear Zone, its evolution is linked to the tectonics between the southern, Europe-derived Tisza unit, the northern ALCAPA block of South Alpine affinity and sheared remnants of Dinaric rocks in between (Csontos & Nagymarosy 1998, Fodor et al. 1999, Csontos & Vörös 2004).

During the Early to Middle Miocene, a flexural basin related to the convergent thrusting of Tisza- (or Dinaric-) and ALCAPA-derived units was created. On the southern side of the basin, N-NW vergent thrust sheets were observed. On the opposite front, Triassic carbonates of ALCAPA were thrust several kilometres above Palaeogene formations to the SW.

Local deposition of Late Middle Miocene (Badenian or Sarmatian) salt in the basin (at present almost 200 m in a well at the basin margin) created an ideal detachment surface for all later tectonic processes.

Earliest Late Miocene sinistral strike-slip faulting propagated from the NE (Palotai & Csontos 2010) to create a pull-apart basin above that part of the earlier flexural basin that has not been overthrust. The margins of the basin were generally the fronts of earlier thrusts. While the fault zone on the northwestern margin showed clearly sinistral *en echelon* features, the eastern basin margin is assumed to have acted mainly as a normal fault zone. Faults on both basin margins detached on the salt, which took up the gross deformation of the fault zone. This resulted in the termination of strike-slip to the SW.

Within the pull-apart basin, the ramp-flat geometry of the salt detachment resulted in a set of roll-over anticlines. Alternatively, these features can be regarded as detachment folds related to salt welding.

During the early Late Miocene, strain was partitioned among (1) ongoing north-south oriented soft-linked reverse faulting on both the more significant southern and the less pronounced northern basin margin, and (2) sinistral strike-slip on the northwestern side.

Thrusting ceased at the end of early Late Miocene. The basin continued to subside until the end of Miocene by combining the effects of strike-slip tectonics and compaction. No clear evidence for neotectonic activity has been found in the study area.

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Acknowledgements: MOL, OTKA K81530 & K73195, Midland Valley, SMT.

Three-Dimensional Fold Geometries in N Iraq and SE Turkey: Oblique Collision between Arabia and Eurasia

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The Zagros-Taurus fold and thrust belt developed in response to late Mesozoic ophiolite obduction and Cenozoic oblique continental collision between Arabia and Eurasia. Many of the resultant folds are large elongate four-way closing structures that are easily delineated in regional satellite data. However, the relatively simple first-order fold geometry seen at regional scales often masks considerable structural complexity when viewed in more detail, including scales that are important in predicting the performance of potential hydrocarbons systems. Typical complexity includes very rapid along-strike variation of geometrical fold parameters, including: the dip of fold limbs (from shallow, to upright, to overturned); the number of anticlinal fold hinges (i.e. parts of some folds have box-like geometries, with multiple straight-limb segments and narrow hinge zones; others have more rounded profiles); and fold tightness (open, to tight, isoclinal, and elasticas). Apparent along-strike differences in stratigraphic thickness may not necessarily be caused by primary depositional variations, but in places may be due to high mobility of incompetent mud-prone units, which have high competency contrast relative to the regionally extensive carbonates which appear to control the mechanical stratigraphy. Further structural complexity arises due to the difficulty of accommodating shortening when folds die out laterally, and also due to interactions between adjacent, overlapping periclinal folds. This emphasises that fold geometries seen in 2D are not a reliable indicator of trap potential or effective fold amplitude. Although appraisal methods based on analysis of satellite data are extremely powerful, in general, three-dimensional fold structures cannot be adequately understood without field work to constrain interpretations.

Fracture sealing utilising microbially induced carbonate precipitation.

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Predicting and controlling spatial and temporal variations in fracture flow properties is of considerable importance to the nuclear waste disposal, carbon capture and storage, and hydrocarbon industries. Fractures and faults provide pathways which may allow the migration of contaminants from depth to the surface. The hydraulic properties of fractures are governed by the interactions between the evolving stress field and the continuous precipitation and dissolution of minerals transported via subsurface fluids. Fractures may be subject to multiple mineralisation episodes, between which they may seal completely before being subject to further shear failure or they may remain open pathways for fluid flow and contaminant transport.

We investigate experimentally the spatial and temporal evolution of carbonate precipitation in fractures. We use microbially mediated reactions to reproduce precipitation events similar to those that may be found in fractured rocks. A series of laboratory experiments was carried out using transparent idealised fracture networks to investigate how repeated carbonate precipitation events result in spatial and temporal evolution of the fracture aperture distribution. Fractures were represented as a series of precision-etched parallel channels between a pair of sealed Perspex plates. Multiple channels were designed to maintain a constant flow rate, whilst independently adjusting channel aperture and width to explore the effects of aperture and fluid velocity on biomineral precipitation. The results from these experiments show that both velocity and aperture have important effects on precipitation patterns and rates. For a given flow rate, narrow aperture channels exhibit increased precipitation. Within wide fractures, the pattern of precipitation over time is such that flow is focussed along a gradually decreasing number of discrete tortuous channels (within the fracture plane). Experiments also show that above a certain threshold velocity, precipitation can no longer occur.

These experiments have important consequences for understanding fluid flow and contaminant migration within the crust. They imply that, for bio-mineral processes at least, after each mechanical failure of the crust, regional fracture networks may gradually reduce to form a small number of discrete stable pathways within which the velocity exceeds a given threshold value that prohibits further mineralisation.

Textural modification and deformation related to faulting in chalk rocks

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During fault or fracture propagation in the brittle field, deformation is distributed along several discontinuities. Generally in the first steps, tension cracks and shear fractures, are formed, depending on the mechanical conditions and heterogeneities (lithology, cementation, thickness variations). Various associations of fractures may develop and produce different patterns, with transpression and transtension zones with consistent orientations. Chalk is a homogeneous rock where strong deformation at the grain level is associated with faulting. In Campanian white chalk and Maastrichtian phosphatic calcarenite , texture modifications were documented and analysed in samples related to synsedimentary movement of normal fault. Most of the time, within a 5 to 10 cm thick fringe on each side of normal faults, modifications of texture and correlative petrophysical properties were deduced.

Using SEM observations, image analysis, reconstruction of the porous media and physical measurements, textural modifications are constraint in relation with the faulting process. Dissolution and cementation features, together with a reorganisation of the pore space near the faults plane can be explained by massive fluid transfers. Faulting is interpreted as ductile shearing, which involves slip and dissolution first in shear deformation bands and then along a single fault plane. Displacements beside the main fault are distributed over an increasing number of structures. These structures can be interpreted as sharp discontinuities or deformation bands. In deformation bands the texture of the parent rock is modified. Translation and rotation, fracturing of grains and dissolution are the main modes of deformation at the grain scale. The change in texture commonly produces a small change in porosity. Different size and morphologies of pore can be observed with neoformated mineralization.

In same pattern of fractures, faults or joints, flint filling can be observed. These are connected to the flint levels well known in cretaceous chalk formations. There is a progressive passage between flint and chalk with most of the time a nucleus fracture inside the fractured zone. The observation precise also the timing between flint filling in fractures, flint levels, chalk deposit, fractures and brittle tectonics by the fact that the network of fractures is related to a synsedimentary tectonic event, mainly before the end of Cretaceous.

Slip zone structure and processes in seismogenic carbonate faults

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High velocity rotary shear experiments performed at seismic slip velocities (>1 m/s) have shown that experimental faults are weak; with increasing displacement, friction coefficient values decrease from Byerlee's values (μ = 0.6-0.85) to values of ~0.1-0.2. In carbonate rocks, it has been shown that fault lubrication is due to the operation of multiple dynamic weakening mechanisms (e.g., flash heating, thermal pressurization, nanoparticle lubrication), which are thermally activated due to the frictional heat generated along localized slip surfaces during rapid slip.

The aim of this study has been to investigate whether evidence can be found for these weakening mechanisms operating in a natural fault zone. Field studies were carried out on the active Gubbio fault zone (1984, Mw = 5.6) in the northern Apennines of Italy, where a number of highly localized principal slip surfaces (PSSs) are exposed cutting through Jurassic-Oligocene carbonates. Fault rocks are predominantly breccias and foliated cataclasites, formed at depths of 2.5-3 km.

Preliminary microstructural analyses of the PSSs reveal that slip is localized within very narrow principal slip zones (PSZs), on the order of 10-100 μm thickness. PSZs are composed of very fine ultracataclasite gouge, containing a high proportion of nano-sized particles. The ultracataclasite commonly displays a foliated texture and sub-micron scale zones of extreme shear localization. A broader slip zone, up to 1.5 mm wide and containing multiple slip surfaces, is associated with the most evolved PSSs. Here, the host rock material is heavily fractured, abraded and altered, sometimes with an ultracataclasite matrix. The surrounding wall rock often has a porous texture, and calcite crystals have altered rims with lobate textures, both of which may be indicative of thermally activated chemical reactions. Occasionally, mantled clasts are observed: central, sub-rounded clasts of calcite, or polymineralic clasts of calcite and clay particles, enclosed by a cortex of ultracataclasite. These may be a product of thermal pressurization in the slip zone.

These microstructures are compared to those in experimentally deformed dolomite gouges, and the slip zone features are found to be strikingly similar. It is clear that as slip accumulates along PSSs, well-developed PSZs are formed with well-defined foliations and R- and Y-shears, indicating progressive localization of deformation. The similarities between the two sets of samples implies that the dynamic weakening mechanisms known to occur in experimental carbonate slip zones are indeed likely to be in operation in their naturally occurring counterparts.

Experimental deformation of calcite fault gouges at high normal stress and sliding velocity

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In recent years several experimental studies have been performed using rotary-shear apparatus to investigate the frictional behavior of gouge materials at seismic slip rates. However, because of technical difficulties confining gouge layers, a majority of these experiments were conducted at normal stresses <2-3MPa, making extrapolation to natural conditions challenging. Here, we present results from an experimental study on calcite gouges (<250μm grain size) deformed in a purpose-built sample holder and using a rotary-shear apparatus at INGV, Rome. Ring-shaped (25/45mm int./ext. diameter), 2.8mm-thick layers of gouge were deformed up to 34MPa normal stress, at slip rates of 10μm/s - 3m/s, in both room-dry and water-present conditions. A peak slip rate of 3m/s was achieved after 0.5s, and total displacements were 1-3m. CO_2 emissions were monitored using a mass spectrometer connected to a capillary tube positioned approximately 1cm from the gouge sample holder. Samples were preserved in ultra-low viscosity resin for optical and Field-Emission SEM observations.

At slip rates >0.3m/s frictional strength, μ, increases to a peak value of 0.6-1.0 followed by a rapid decay to a lower steady-state value, μ_{ss}, before finally undergoing dynamic strength recovery during decelerating slip. CO_2 starts to be liberated almost instantaneously (within 500μm of slip) during acceleration and reaches a peak value during steady-state sliding of up to 10,000ppm, before decreasing to 380-420ppm within a few seconds following the experiment. μ_{ss} decreases with increasing slip rate, but in contrast to previous experiments we find that extremely low values of μ_{ss}<0.2 are only achieved at a slip rate of 1m/s for normal stresses >22MPa. An unexpected result is that steady-state shear stress at slip rates >1m/s does not increase monotonically (either linearly or not, e.g. in the presence of lubrication) with normal stress, but begins to decrease above a normal stress of 15-20MPa, a behavior that may be described as "hyper-lubrication". Gouge layers deformed at slip rates >0.5m/s and normal stresses >11MPa are cut by mirror-like slip surfaces underlain by fine-grained (<1μm) decomposition zones up to 500μm thick. The slip surfaces are lined by interlocking, polygonal grains between 100nm and 2μm in size. Grain boundaries are straight or slightly curved and often make triple-junctions with large interfacial angles. In cross-section, the decomposition zones contain elongate grains up to 20μm long that collectively define a strong shape-preferred orientation inclined in the shear direction. We interpret these and other microstructures to indicate plastic deformation and annealing of the calcite gouges immediately beneath and on the slip-surfaces.

The frictional properties of carbonates gouges at sub-seismic and seismic slip rates

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Field studies conducted on the slip zones of exhumed faults, developed in the same evaporitic sequences as the seismic sources of the Colfiorito earthquakes, suggest that the nucleation and the propagation of seismic events occur in localized slip zones of fine-grained dolomite and calcite fault gouges, characterized by thin slip planes of localized deformation. Recent friction experiments performed on dolomite gouge samples at seismic slip rates have shown that during the propagation of an earthquake, the frictional strength of the material from the initial peak values of 0.65-0.8 dramatically drops to the final values of 0.1 - 0.2 . This study reports of low and high velocity rotary shear experiments on carbonate gouges (dolomite and calcite) tested at room temperature and humidity, for a range of slip rates typical of those attained by seismogenic faults during the seismic cycle. Stress vs. strain curves obtained during sliding experiments at constant sub-seismic slip rates (ranging from 13.4 μm/s to1.34 mm/s) and normal stresses (ranging between 2 and 20 MPa) show initial strain hardening behaviour for both materials till the attainment of peak stress values, which are in turn followed by strain weakening behaviour and steady state stress at constant values. This behaviour is typical of consolidated or slightly overconsolidated granular materials. Cyclic slide-hold-slide experiments at subseismic slip rates show that friction increases with hold time according to a logarithmic relationship. The healing rates obtained from our experiments, when extrapolated to seismogenic depths of the M=6 Colfiorito earthquakes, match the static stress drops estimated from seismological data. Velocity step experiments show velocity strengthening behaviour for the entire tested range of slip rates (subseismic regime), normal stresses and displacements. Experiments performed at seismic slip rates show dramatic weakening, with measured friction coefficients which are as low as 0.2. Velocity step experiments performed on samples which experienced sliding at seismic slip rates show a transition from velocity strengthening to velocity weakening behaviour at normal stresses larger than 12 MPa, after a holding period of 1000 sec. During the same experiments, the behaviour of the gouge material is velocity strengthening for smaller holding times. The dependence of the observed rate and states behaviour on the healing process following sliding at seismic slip rates is unclear and still under investigation. Nevertheless, these preliminary results may have strong implications for earthquake nucleation, as the propagation of a seismic rupture through velocity strengthening rocks may change their behaviour and favour earthquake nucleation. Our preliminary data also have significant implications for rupture propagation and afterslip processes as, depending on the healing time, fault zones developed in unconsolidated sediments may be either characterized by velocity strengthening behaviour, which may cause rupture arrest and afterslip, or velocity weakening behaviour, which may facilitate rupture propagation to the surface.

A comparison of cumulative vs. incremental fault growth derived from high-resolution LiDAR and InSAR data of the Dabbahu segment, Afar, Ethiopia.

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The influence of magma in extensional tectonic settings is widely recognised. Magmatic intrusions can cause surface fault displacement in the range of meters accompanied by only moderate seismicity. The nature of fault growth generally enables us to study only a static image of its evolution. The Dabbahu (Afar) rifting episode, which commenced in 2005 within the Afar Depression, is providing a unique opportunity to study progressive magmatically-driven fault growth. Since its onset, a total of 14 individual dyking events have been identified through InSAR and seismicity intruding the same section of the segment.

In addition to InSAR observations, a high-resolution airborne LiDAR survey was carried out in October 2009 covering the central section of the Dabbahu segment. The resulting Digital Elevation Model (DEM) covers 800 km2 with a resolution of 0.5m. This enables us to process InSAR data at higher resolution. We calculate interferograms covering four of the dyke intrusions using L-band (23.6 cm wavelength) radar data from the ALOS satellite. These provide better coherence over the area of faulting and simplify the complex phase unwrapping problem. We use the interferograms to estimate the slip on some of the faults that occurred during the dyke intrusions. Here we present preliminary results comparing the observed incremental slip with the cumulative fault displacement-length patterns which have been extracted automatically from the LiDAR DEM.

The role of reactivation and fluid pressure cycling in the development of late zeolite-bearing faults and fractures from the Adamello batholith, Italy

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Interconnected networks of faults and veins filled with zeolites and other minerals are a common feature of many granitic rocks, including deformed plutons and regions of high grade continental basement. Typically the fracture fills formed late in the tectonic history and at relatively low temperatures (e.g. < 200°) and appear to represent a final phase of fluid flow and mineralisation developed during the final stages of exhumation. In the northern part of the Adamello pluton in the Italian Alps, a geometrically complex and kinematically diverse set of zeolite bearing faults and veins is well exposed in the deformed tonalites associated with the Gole Larghe Fault Zone (GLFZ). These features post date all other deformation structures in the pluton, including cooling joints formed at T> 550°, ductile shear zones active at 550° > T > 450°and the assemblage of faults, cataclasites and pseudotachylytes formed at 300° > T > 250° associated with the GLFZ. Three main groups of zeolite-bearing fractures are recognised based on differences in orientation and kinematics of associated shear fracture displacements. These are: i) E-W sinistral reverse thrusts; ii) NNE-SSW sinistral normal faults; and iii) NNW-SSE normal faults. All three groups are associated with the development of white, yellow and red-orange zeolite-rich veins and fault gouge. Individual fault zones are rarely more than a few metres wide and fault offsets are generally small (mostly < 5m). Minor fractures associated with each group display mutually cross-cutting relationships consistent with them all being broadly contemporaneous features. This is confirmed by thin section and XRD analyses which reveal a fairly uniform set of mineral fills including laumontite, stilbite, scolecite and rare prehenite. All three fracture groups are hard linked, locally forming spectacular mineralised fracture meshes. These features, together with the local injection of zeolite-rich gouge into tensile fractures in the footwall of the largest E-W thrust point to the cyclic development of significant fluid overpressures at the time of active faulting. The geometry, kinematics and location of the zeolite-rich fractures appears to be very significantly influenced by the presence of pre-existing sets of cooling joints, ductile shear zones, and fractures and faults associated with the GLFZ. The apparent synchronicity of the E-W thrusts and the other fracture sets is problematic and requires either a periodic switching of local or regional stress/strain axes to occur during faulting or a complex mesh of accommodation structures.

The evolution of fault zones in basalt: predicting internal structure, petrophysical properties and effect on fluid flow.

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Interest in the architecture and fluid flow potential of fault zones in crystalline rock has intensified over recent years, due to their importance to the hydrocarbon industry, carbon storage, and radioactive waste storage. Although some 30% of hydrocarbon plays within igneous rocks are contained within basalt, and basalt has been proposed as a host rock for CO_2 storage, little work has focused on the evolution of faults in basalt. Constraining the mechanisms of fault growth and evolution allows us to place constraints on the likely across- and along- fault flow properties of the bulk fault zone. Here we present a new detailed field-data derived model for sub-surface fault rock evolution in basalts, based on fieldwork in the North Atlantic Igneous Province (Scotland, the Faroe Islands and Iceland). The faults have offsets from <1m to >100m, and cut basaltic lava flows, and interbeds of volcaniclastic and sedimentary rocks.

Faults with offset of <1m are observed to have grown by fracture linkage and propagation, with narrow fracture-bound breccia zones forming *in situ*. At higher displacements (1-24m), multiple slip surfaces develop and breccia zones break down into micro breccias and cataclasites. Fracturing in the fault walls create coarse protobreccias that are consumed by the fault with increasing growth, leading to a widening of the overall fault zone. Larger displacements (>25m) are accommodated on dominant through-going slip surfaces with the development of foliated cataclasites. Continued breakdown of the wall rock leads to increasing fault zone width and continuing evolution of fault rocks along subsidiary slip surfaces. In parallel with the mechanical breakdown of the host rock, chemical breakdown of the basalt assists in fault rock formation. In the lowest offset faults, groundmass in the wallrock is altered to clays and fracture surfaces are coated with clay. As deformation progresses, feldspar phenocrysts increasingly alter to clays. These clays form the matrix to breccias and cataclasites and concentrate along fractures and minor slip surfaces.

This fault evolution model implies that with increasing displacements, the system evolves from a conduit to conduit-barrier system. At lower (0-1m) displacements, the predominance of open fracture development and limited clay formation would result in faults having a higher permeability than the host rock. Clay formation could block original flow pathways (i.e. slip surfaces and fractures), but flow could still occur in higher porosity zones such as unsealed fractures and breccia zones within the fault. At high displacements (>25m), the presence of highly comminuted, clay-rich fault rocks and clay-coated slip surfaces will tend to progressively reduce the across-fault bulk permeability. Progressive brecciation of the wall rocks and continuous production of slip surfaces could potentially provide high permeability pathways through this increasingly complex fault zone and increase along-fault permeability. This detailed work on the mechanisms of fault rock development will ultimately allow us to make predictions of fault zone permeability at depth.

Fault zone architecture and permeability structure evolution in basalts

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Fluid flow in upper-crustal brittle fault zones is dependent on the permeability of the fault rock assemblage and its architecture. Here we present a combined field, microstructural and experimental characterization of basalt-hosted fault zones from the Faroe Islands in order to determine the permeability structure and permeability evolution of faults in basalts. Samples that are representative of the various fault zone components are used for experimental measurement of the permeability structure of faults in basalts. Results indicate that, within the effective pressure range (10-90 MPa: equivalent to ~0.3 to ~3.0 km depth), basalt-hosted faults evolve from relatively low-permeability mm-cm-scale displacement structures (e.g. ~9.47×10^{-18} to 3.40×10^{-19} m^2), to relatively high-permeability metre-scale displacement structures (e.g. ~10^{-15} to 1.4×10^{-16} m^2). The highest permeabilities occur within mineralized chaotic breccia fault cores. In dam-scale displacement faults, the fault core permeability reduces (e.g. ~5.4×10^{-18} to 2.8×10^{-18} m^2), but remains up to three orders of magnitude more permeable than the surrounding damage zone and undeformed host rock. Micro-structural analyses reveal the bulk permeability is controlled by fault-parallel clay generation (decreasing permeability) and zeolite/calcite mineral vein connectivity (increasing permeability). Along-fault fluid flow is increased relative to the host rock, whilst cross-fault permeability is low throughout fault rock evolution. This fault permeability structure in basalt piles will promote cross-fault compartmentalization, with along-fault flow facilitating migration between relatively high-permeability units, and bypassing the bulk of the stratigraphy.

Deriving fault slip histories from cosmogenic exposure ages along bedrock fault scarps

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Cosmogenic surface exposure dating is a powerful tool for reconstructing long-term slip rates on active faults and can provide evidence for temporal earthquake clustering. Extensional faults are particularly amenable to this type of study because they commonly produce a striated bedrock scarp, exhumed by faulting, that can be sampled to obtain the concentration profile of a cosmogenic isotope as a function of fault-throw. Here we compare modelling results of a synthetic dataset of known slip history with that derived from a suite of *in situ* ^{36}Cl concentration profiles sampled from carbonate normal fault scarps.

Existing methods for extracting paleo-earthquake records from such data use forward modelling and conclude that individual slip events ≥1m (≥ Magnitude 7.0) may be resolved, although a cluster of smaller magnitude events can produce a similar ^{36}Cl profile. Due to uneven scarp preservation sample spacing in real data sets is variable (up to 10's cm), further limiting our ability to extract tectonic information.

We use Monte Carlo inversion on synthetic ^{36}Cl datasets to investigate the effect of sample spacing and analytical error on the interpretation of fault slip histories (i.e. number of earthquakes, timing, magnitude of slip) and show how sample density and analytical error influence our interpretation of the true slip history of a fault.

The conclusions drawn from our analysis of the synthetic data then guide our inversion of real ^{36}Cl concentration profiles, derived from active normal fault scarps in Abruzzo, central Italy. We couple our data with LiDAR and sub-surface GPR to constrain the Holocene slip history of the faults and discuss the implications and limitations for deriving slip variability and earthquake hazards in the region.

Abstracts of Poster Presentations

Landscape and tectonics of the Greater Caucasus

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Abstract:

The Greater Caucasus is to the northwest of the South Caspian Basin and connects the Caspian Sea with the Black Sea. The range extends for approximately one thousand kilometres, northwest–southeast. The mountain range is a part of the Alpine–Himalayan orogenic belt, and was created as a result of the Arabia Eurasia-plate collision.

Using the data acquired from the Shuttle Radar Topography Mission digital elevation models, topographic characteristics of the Greater Caucasus have been quantified from northwest to southeast. Using Arc Map and RiScan software, 900 profiles for elevation and slope have been constructed across the Greater Caucasus, with a distance of 1000 metre between neighbouring sections. Elevation and slope and values longitudinal for maximum, minimum and average have been plotted to show topographic changes. By using Move software and geological maps of the Greater Caucasus, geological cross section have been constructed NE-SW in the middle of the belt to show the correlation between the tectonics and the surface processes.

Even though, the Greater Caucasus region is not broad, it is a high range, with maximum altitudes of more than 4000 m above sea level close to its core for about 500 kilometre NW-SE. This maximum elevation decreases rapidly as we head southeast towards the coast of the Caspian Sea and the Apsheron peninsula and west to the Black Sea, we divide the Greater Caucasus into three parts. The central part represents a “study-state” condition, where convergence, thickening and exhumation continue, but are balanced by erosion. The lateral ranges are effectively snap-shots of a mountain belt in the process of growing towards the study-state condition. To further investigate the relationship between the tectonics and the surface processes, we are working to compare the Greater Caucasus as an active belt and the Pyrenees Mountains (in the border between France and Spain) which is as narrow as the Greater Caucasus, but is an inactive belt. This comparison will be done by creating about 500 sections or profiles for the elevation and slope of the Pyrenees.

Exploring the Complex Origins of Orogenic Plateau Magmatism

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Magmatism is a common feature of high plateaux created during continental collision, but the causes remain enigmatic. Here we study Plio-Quaternary volcanics from the active Arabia-Eurasia collision zone, to determine the chemistry of these rocks and their relations to faulting and deeper lithospheric structure. The great majority of the centres lie within the overriding Eurasian plate in Iran, eastern Turkey and Armenia , implying that mantle fertilised by pre-collision subduction processes plays a significant role in magma generation. The composition of the Plio-Quaternary centres is extremely variable, ranging from OIB-like alkali basalts, to intermediate types resembling mature continental arc lavas, to potassic and even ultrapotassic lavas. These centres are erupted across a mosaic of pre-Cenozoic suture zones and heterogeneous lithospheric blocks. The chemical diversity implies a range of partial melting conditions operating on lithospheric and perhaps sub-lithospheric sources. Published data show a thick (>200 km) lithospheric keel beneath the Arabia-Eurasia suture, thinning to near normal thicknesses (~120 km) across much of central and northern Iran. Thin mantle lithosphere under eastern Turkey (max. ~30 km) may relate to the region's juvenile, accretionary lithosphere. These variable thicknesses are constraints on the cause of the melting in each area, and the degree of variation suggests that no one mechanism applies across the plateau. Various melting models have been suggested. Break-off of the subducted Neo-Tethyan oceanic slab is supported by tomographic data, which may have permitted melting related to adiabatic ascent of hot asthenosphere under areas where the lithosphere is thin. This seems a less plausible mechanism where the lithosphere is at normal or greater than normal thickness. The same problem applies to postulated lower lithosphere delamination. Isolated pull-aparts may account for the location of some centres, but are not generally applicable as melt triggers. Enigmatic lavas are erupted over the thick lithosphere of Kurdistan Province, Iran. These alkali basalts and basanites have the chemical characteristics of small degree (<1%) melts in the garnet stability field. Most possess supra-subduction zone chemistry (La/Nb = 1-3), but this signature is highly variable. Modelling suggests the depletion of residual amphibole during the progression of partial melting can explain the observed La/Nb range. This melting may occur as the result of lithospheric thickening. At depths of ~90 km, amphibole-bearing peridotite crosses an experimentally-determined "backbend" in its solidus. Melting can continue while the source remains hydrated. Such "compression" melting may apply to parts of other orogenic plateaux, including Tibet.

Seiche-triggered deformation of offshore sediments

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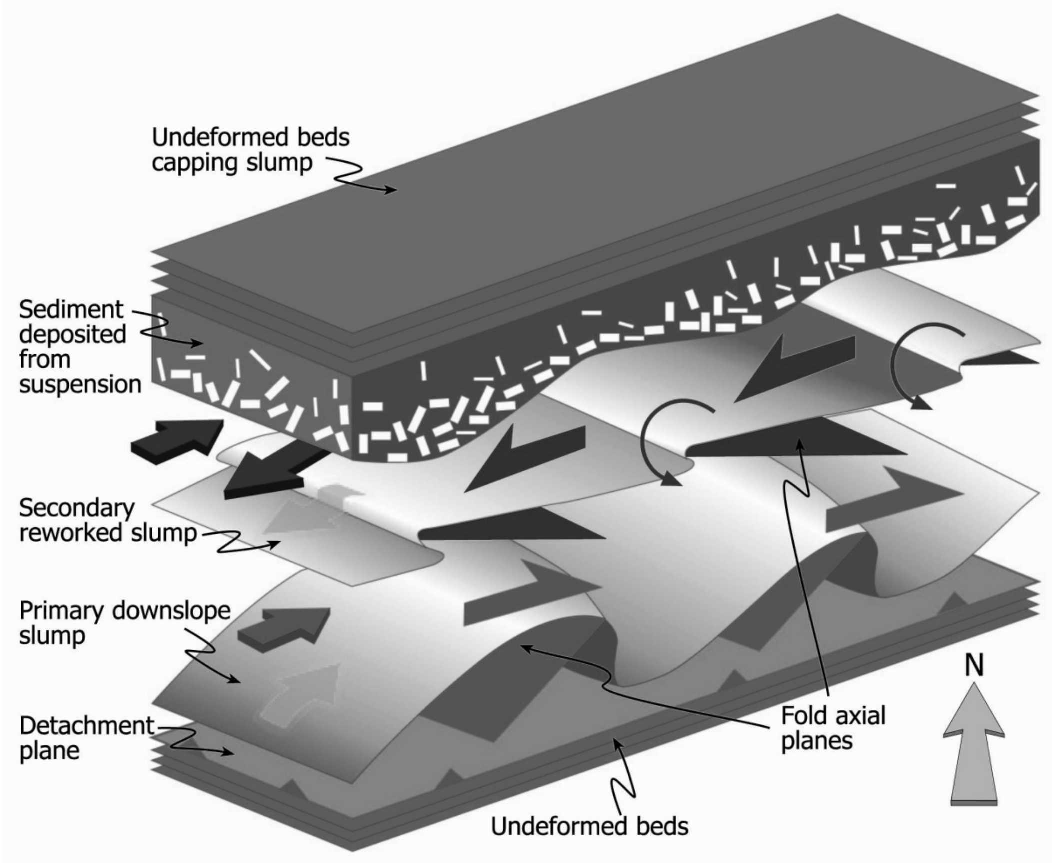
Most studies of tsunami and seiche related deposits have focussed on coastal and near coastal zones which are most readily accessible, with few investigations of deeper water settings and the potential soft-sediment deformation effects of such waves. The Late Pleistocene Lisan Fm. outcropping to the west of the Dead Sea contains superb examples of sedimentary slump folds formed in water depths of <100m. We have collected new structural data from an individual horizon that demonstrate that these gravity-driven slumps may be coaxially refolded and reworked by sheared folds and thrusts verging both back up and then down the palaeoslope. This suggests that it is possible to generate up-slope flow of material in some circumstances. A progressive increase in reworking and shearing is developed up through the folded sediment, culminating in a breccia layer that is capped by a thin, typically graded horizon of undeformed silt and sand. We suggest that these sequentially reworked deposits are consistent with seismically triggered tsunami and seiche waves that would flow back and forth across the main slump horizon triggered by the same earthquake. The overlying sands and silts that infill local topography are considered to be deposited from turbid suspension during cessation of wave action and represent homogenite deposits (see below). Although tsunami and seiche waves have previously been both numerically modelled and directly witnessed in the Dead Sea Basin, this study forms the first detailed structural analysis and interpretation of potential reworking associated with such waves in offshore settings.



Quantifying Patterns of Deformation Bands: Examples from the Hopeman Sandstone, Moray, Scotland

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The attributes of fractures and their patterns, such as orientation, intensity, size, and shape can have significant effects on hydrocarbon reservoir and aquifer performance. The quantification of fracture attributes and their patterns in outcrop analogues can guide the construction of testable expressions for multidimensional scaling relationships, and their application to the subsurface.

Cataclastic deformation bands and their patterns have been mapped and quantified in outcrops of the Hopeman Sandstone in Moray, northern Scotland. These aeolian sandstones are of Permian age and are cut by brittle structures believed to be Jurassic in age. Fracture attribute data have been collected from sub-horizontal wave cut platforms and sub-vertical faces of sea stacks and cliffs. Fracture intensity, density and mean trace lengths have all been estimated through the application of scanlines with a circular scan window.

The collection of these datasets from 3 approximately orthogonal planes allows us to test scaling relationships from 1D to 3D. We explore the scaling and distribution of attributes such as size and orientation. Fractal scaling laws are often based on an assumption of random spatial locations, but for clustered patterns of deformation bands these laws require modification.

Use of digital technology to aid 3D visualisation of Earth structures in the field and laboratory.

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The ability to visualise 3D Earth structures such as unconformities, faults, and igneous intrusions is an inherent part of Earth Science. But it is a skill that many students find challenging. Visualisation in 3D is important for resource and storage development and it is this type of skill that is in demand for future environment and energy challenges, such as the sub-surface storage of CO_2, radioactive waste, and water. Traditionally teaching of 3D visualisation has relied on 2D paper exercises in the laboratory, augmented by field courses where students see how structures mapped in 2D intersect topography. However, visualising how these structures extend into the sub-surface is still difficult for many students. The 2D exercises are too abstract and therefore they do not build the required skills. Digital technology in the form of 3D geological models provides a potential solution to help students develop the 3D visualisation required for a successful geological career.

In a project funded by the Geography, Earth and Environmental Science (GEES) Subject Centre of the Higher Education Academy, the authors will produce digital 3D models of Earth structures from classic localities. The project will combine this investment in the development of digital teaching materials with pedagogic research into the effectiveness of digital 3D visualisation for the understanding of Earth structures (and their 4D evolution). The models and associated teaching materials will be freely available online for use by HEIs. At the start of this project we are seeking input from Earth Scientists' at HEIs on teaching challenges in this area and on potential localities for the 3D models. Associated with these models will be pedagogic research on their effectiveness as a teaching tool for the 3D visualisation of Earth structures in the field and laboratory and their impact on students' learning experiences to feedback into course development and community best practice.

Structural geology: *how* should we be teaching undergraduates?

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As a fundamentally three-dimensional (four-dimensional, including time) subject, *Structural Geology and Tectonics* present a pedagogical challenge: how easily do undergraduate students grasp 3-D concepts and how do we practically assess this, and which combination of resources and teaching style result in successful learning? For example, is it a necessity to include state-of-the-art computer-generated 3- or 4-D animations and more practical-based classes (including fieldtrips) rather than 2-D images (text books) and theory-based lectures? As instructors, how much does our individual approach in understanding structural geology influence how we teach it, and should we be prepared to teach from a variety of perspectives, e.g. visual/conceptual/qualitative versus mathematical/quantitative so as to cover all possible learning styles?

This presentation will explore these kinds of pedagogic issues from the perspective of an early career researcher and teaching fellow in Earth Sciences, teaching at a Scottish university wherein undergraduates spend the first two years ('Sub-Honours') taking modules in Earth Sciences alongside another two (1st year) and then one (2nd year) other degree subjects. How to effectively use the limited time in Sub-Honours, whilst still building a firm foundation for Honours level structural geology will be discussed, and conclude with possible changes to the present curriculum including consideration of financial and staff time constraints. Feedback from current undergraduates and recent graduates will be combined with an evaluation of individual learning styles to explore how confidence in structural geological skills are obtained, and where (in the classroom or in the field), when (within the undergraduate degree) and how (student- or tutor-led, in conjunction with which resources) they reach 'Eureka!' moments.

This presentation directly complements the lunchtime discussion on "Structural Geology: *what* should we be teaching undergraduates?".

Investigating the controls on porosity and permeability development in unconventional igneous oil and gas reservoirs

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Volcanic rocks are becoming increasingly recognized as viable petroleum reservoirs, with recent discoveries including the Miocene Minami-Nagaoka gas field in the Niigata basin, Japan, the Early Tertiary Padra oil field in India, and various Jurassic fields within the Austral basin of southern Argentina. Reservoir quality in these sequences is primarily controlled by porosity and permeability, which can be evaluated petrophysically through laboratory based measurements. Although porosities can commonly be relatively high in such rocks the permeabilities are often very low making it difficult to extract the hydrocarbons. The porosity/permeability characteristics can be modified by a number of secondary processes including fracturing due to tectonism and/or alteration due to metamorphism, meteoric or hydrothermal alteration.

X-Ray Computed Tomography is currently being evaluated as a potential tool to help more fully understand the controls on porosity-permeability development in a suite of variably altered Cretaceous volcanic rocks from South America. Basalts, andesites and rhyolites have been investigated to produce a qualitative visualization of the 3D pore structure, and a quantitative estimate of porosity. Integrating these high-resolution porosity maps with the results from more routine petrographical evaluation has permitted the evolution and nature of porosity development in these volcanic rocks to be better understood. Moreover, these porosity values can be compared with the results obtained from traditional petrophysical analysis so as to assess the potential industrial application of this new technique.

Natural Slip Surfaces in Fault Cores of Seismogenic Carbonate Faults

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Observations from drilled fault cores of major active fault zones show that seismic slip is localized within narrow slip zones (1-5 mm) of fine-grained fault rocks. The evolution with slip rate and displacement of the frictional properties of the slip surfaces and the adjacent fault rocks, they develop within, controls the propagation of an earthquake. Recent friction experiments performed on a variety of rock types at seismic slip rates have shown a dramatic drop of frictional strength (f = 0.1 - 0.2) from the initial peak values in the Byerlee's range (f = 0.65 - 0.8). Despite an overwhelming number of laboratory data showing dynamic lubrication of experimental faults at seismic slip rates, the mechanical properties of natural slip zones and associated slip surfaces are still poorly understood. Furthermore, there is still a paucity of field observations from natural slip zones of active faults, which may be related to the thermally activated rupture propagation processes.
We studied 11 fault segments of three well-exposed extensional fault systems in the northern Apennines of Italy: the Umbria Fault system, the L'Aquila Fault system and the Fucino Basin fault system. These fault systems are located along the NW-SE oriented seismic belt of the northern Apennines of Italy, which has produced moderate/large earthquakes ($5<M<7$). Field studies show that the large scale fault geometry is given by a damage zone and a fault core. The fault core/damage zone transition is sharp; most of the displacement is accommodated within the fault cores, which are from few to tens of meters thick. The fault cores internal architecture is complex and made of fault parallel domains (up to few meters thick) of fault breccias, fine to coarse grained cataclasites and fault gouges. Within the fault core, slip is further localized in narrow slip zones bounded on one side by principal slip surfaces, which appear as polished and striated planes. Slip localization has been observed both at the boundary between two different fault rock domains and within a homogeneous fault rock domain.
Microstructural analyses will be performed on samples of fault rocks and slip zones, collected from the different fault core domains, to infer the dominant deformation mechanisms. Friction experiments will be performed, for a range of normal stresses (1-20 MPa), on the different type of fault rocks and the natural slip surfaces to characterize their frictional behaviour at constant (strain hardening/weakening) and variable (velocity weakening/strengthening) sub-seismic slip rates (microns/s) and at seismic slip rates (1 m/s). Grain size particle analyses and porosity data on fault rock samples will be used to quantitatively compare field and laboratory fault rocks.

The timing and controls of salt wall collapse in the Central Graben of the North Sea.

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Collapsed salt walls are found throughout the Central Graben of the North Sea. These form important hydrocarbon plays of Upper Jurassic age, such as the Ula, Tambar and Gyda fields. The salt walls formed as a result of Triassic deposition and collapsed during North Sea rifting during the Upper Jurassic and Lower Cretaceous. Previous studies of the collapse have only noted the timing of collapse but not its specific controls and have not noted the 3-dimensional variations of salt wall morphology. The present study uses restorations of collapsed salt walls to provide a visual geological history of the growth and collapse of a salt wall. 3D modelling provides an excellent visualisation of the variations along strike of a salt wall and its links to underlying rifting.

Restorations were undertaken using LithoTect and TrapTester was used for 3D models. Restorations show the salt walls collapsed in two stages, firstly during Upper Jurassic rifting and then during Lower Cretaceous thermal subsidence. They also show the deformation occurring in salt wall-surrounded mini-basins. Mini-basins are force-folded after grounding on the footwalls of basement rift faults during Upper Jurassic rifting.

3D modelling shows the relationship of salt wall collapse to underlying basement faults; a wide salt wall is often found above a wide fault terrace zone and a narrow salt wall forms above a narrow fault zone. Regional extension causes collapse where there is no underlying faulting; however localised extension across a fault zone underlying the salt wall controls the amount of collapse, with a narrow fault zone causing a deep collapse.

There is plenty of scope for further work in relation to this subject, including: 1. further 2D and 3D restorations; 2. comparison of observed structures and forward modelling of restorations with physical and geomechanical modelling; 3. a sub-seismic study into the sealing behaviour of collapse grabens and the surrounding basins juxtaposed by collapse and 4. the pressure behaviour of collapse grabens.

Micromechanics of normal fault initiation: the Fasagh Fault Zone, NW Scotland

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Cataclasis dominates as a deformation process under upper crustal conditions where temperatures and pressures are not high enough to allow fully ductile deformation mechanisms to take place. However, rocks can behave in a ductile manner either on the whole-rock (e.g. cataclastic flow) or sub-grain scales (e.g. low-temperature plasticity). The brittle processes that contribute to cataclasis, such as microcracking, are well documented but less work has been conducted on both intra-grain processes and the crystallographic orientation of individual grains during fault initiation and development.

Cataclasis is generally thought of as being a disordering process but results from the present study suggest that this may not be entirely the case. The fault studied is a splay of the regional-scale Fasagh normal fault, which is situated in the foreland immediately adjacent to the sole thrust of the Moine Thrust Zone, Kishorn, NW Highlands. The splay fault juxtaposes An t-Sron Formation Fucoid Beds in the hangingwall against Eriboll Quartzite in the footwall.

Several methods of study have been used in order to gain a more detailed understanding of the initiation of normal faulting in the quartzite. Optical and SEM-cathodoluminescence (CL) microscopy were used to observe and identify microstructures whilst SEM-EBSD was used to determine crystallographic orientations and the presence of dauphiné twins.

Initial results suggest that cataclasis in quartz, at least in its early stages, does not completely disorder grain crystallographic orientations and can actually serve to increase crystallographic preferred orientation (CPO). Dauphiné twinning is also observed to be an extremely common feature. It is present in virtually all grains, not only at grain boundaries (due to grain-to-grain contact) but also as elongate features within grains. Although further work is needed, it is proposed that dauphiné twins of the latter type may develop as the first stage of a process that leads eventually to the formation of intragranular microcracks that subsequently promote cataclasis and fault rock formation.

Porosity around Fault Zones: Correlations Between Fault Zone Architecture and Petrophysical Properties

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Normal faulting in highly porous aeolian sandstones develops from zones of composite deformation bands recording many accumulated slip events (Aydin and Johnson, 1983). The efficiency of deformation bands as baffles or conduits to fluid flow depends on the thickness of the composite deformation bands and on the petrophysical properties of the deformation bands and surrounding rock. Increases in porosity associated with faulting can be due to microfractures in the damage zone and dilatancy associated with cataclasis in the fault core. Porosity decreases can occur during faulting due to cementation, dissolution, cataclasis and pore collapse. Field and experimental evidence shows that fault damage zone porosity, in the form of microfractures is anisotropic and patterned (Anders and Wiltschko, 1994). Pore fluid pressure changes in this fault zone porosity can alter the geomechanical risk and so accurate predictions of fault stability in clastic reservoirs and their top seals are vital for the extraction of hydrocarbons, the injection of water into reservoirs and the storage of CO_2.

Field data has been collected from four exposures located along strike of the Clashach Fault (Moray). This fault is a sub-seismic scale extensional fault that cuts through the Permian aeolian Hopeman Sandstone Formation. The fault damage zone is around 3 m wide, defined by intense fracturing. The fault core comprises fault breccias (showing variable thickness between 10 cm and 100 cm), a cataclasite unit with numerous polished slip surfaces and a composite unit of anastamosing deformation bands. A number of fracture types including individual and composite deformation bands are visible at variable intensities for up to 50 m either side of the main slip surface. Fault damage zone samples were cored and thin sectioned at three orientations (x, y, z) to the fault plane. Initial results from petrophysical analysis indicate directional variations in porosity and permeability with respect to the fault plane and along fault strike.

Detailed maps and sections through fault zone appear to show different stages of fault growth at each locality along the fault strike. In this study, spatial position along strike is used as a proxy for the temporal evolution of the fault, and the observed changes in the fault zone architecture are correlated to the measured poroperm characteristics. This poster describes quantitative spatial and directional variations of fault zone porosity and permeability along strike, and investigates how the inferred relationship between fault zone architecture and rock properties fits with the published models of faulting in highly porous sandstones.

Investigating the glaciotectonic deformation of glacigenic materials through AMS

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The flow of a glacier can produce spectacular structures within the glacier and the associated glacigenic sediments. These structures record strain and can therefore provide insights into how a glacier moves and deforms its underlying sediment. In using traditional structural geology techniques there is great potential to collect strain data and to interpret this in terms of the relevant strain field and identify the glacial processes acting on the material. The current contribution examines the ways in which one technique, the anisotropy of magnetic susceptibility (AMS) can be used and to determine strain intensity and direction, thereby constraining the processes involved in the formation and subsequent deformation of glacial materials.

We use three examples of AMS applied to glacial materials: 1) in a Quaternary example, a mid Pleistocene glacigenic sequence from Norfolk, AMS is has been used to better understand polyphase glaciotectonism, 2) in a Neoproterozoic example from a "Snowball Earth" glaciation in Svalbard, AMS has been used to provide constraints on the genesis of massive diamictite and determine palaeo-ice flow directions revealing new insights into the landsystem of this Neoproterozoic basin, and 3) an active modern glacier, where we have measured the AMS of the glacier ice itself with the aim of testing how stretching direction relate to ice flow.

This work is in its early stages and the preliminary results are very promising and show the potential of the technique in providing a new, non-subjective, fast and inexpensive method of determining fabrics and thus providing a wealth of information on the deformation of glacigenic materials and our understanding of certain glacial processes.

Asymmetric fold within a Quaternary glaciotectonite from Norfolk

Glaciotectonic disruption of rhythmites from a Neoproterozoic "Snowball Earth" glaciation

Isoclinal folding within debris rich basal ice from Tunabreen, Svalbard

Characterising fracture systems within the Lewisian Gneiss Complex, northwest Scotland: An onshore analogue for the Clair Field

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The Clair Field lies in the Faroe-Shetland Basin, with reservoirs in Devonian and Carboniferous sediments overlying and onlapping a basement high that was upfaulted in the Mesozoic. At Clair, the basement is considered an important control on fluid flow and structural development of the field due to its highly fractured nature. Consequently, it is important to characterise fault networks to assess the connected volume within the basement rocks.

Analyses of fault attributes have been undertaken across a range of scales on both the mainland and Hebridean Islands. Fault systems in Lewisian basement and overlying Mesozoic cover sequences have been characterised as an analogue for the Clair Field. This study included analysis of regional NEXTMap® digital elevation models of the mainland and the Hebrides along with studies of seismic attribute maps of the Clair top basement horizon, with the aim of characterising large scale fault patterns, including orientation, density and spacing attributes. Fieldwork has been undertaken on the mainland and the Hebrides in order to characterise fault systems and the tectonic history within Lewisian Gneiss and sedimentary cover sequences. This involves 1-D line sample analysis, and terrestrial laser scanning (LIDAR) to allow analysis of the fault networks in different dimensions. Thin section analyses augment this study.

1-dimensional and 2-dimensional analyses of regional and outcrop scale data show that NE-SW is a predominant fault trend within the Lewisian in both the mainland and Clair Field datasets. Spacing data show variable population distributions, with outcrop data on the mainland and Hebridean Islands showing mainly power-law distributions. These distributions allow us to infer that the outcrop data show scale-invariance for spacing and can therefore be used as an estimate for the fault networks seen at different scales within the Lewisian.

Based on fieldwork observations a brittle deformation history has been reconstructed. In the Outer Hebrides, the presence of the synrift Stornoway Formation has allowed identification of significant brittle faulting that occurred throughout the Mesozoic to as recently as the Tertiary, and this was often affected by the presence of pre-existing structures. Mainland fracture histories are much older with a limited younger set unaffected by previous structures.

Further analyses will determine whether the mainland or the Hebrides provide the closest match for the fault networks seen within the basement and overlying cover sequences of the Clair Field.

A combined rigid/deformable plate tectonic model for the evolution of the Indian Ocean

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Plate tectonic reconstructions are essential for placing geological information in its correct spatial context, understanding depositional environments, defining basin dimensions and evolution, and serve as a basis for palaeogeographic mapping and for palaeo-climate modelling. Traditional 'rigid' plate reconstructions often result in misfits (overlaps and underfits) in the geometries of juxtaposed plate margins when restored to their pre-rift positions. This has been attributed to internal deformation pre- and/or syn- continental break-up. Poorly defined continent-ocean boundaries add to these problems. To date, few studies have integrated continental extension within a global model.

Recent plate tectonic reconstructions based on the relative motions of Africa, Madagascar, India and Antarctica during the break-up of eastern Gondwana have not taken into account the effects of deformation; particularly between India and Madagascar, and India and the Seychelles. A deformable plate model is in development that builds on the current rigid plate model to describe the complex multiphase break-up history between Africa, Madagascar, Seychelles and India, the associated magmatic activity and subsequent India/Eurasia collision.

The break-up of eastern Gondwana occurred in the mid Jurassic by rifting between Africa and the India-Madagascar-Australian-Antarctica plates, followed by the Late Jurassic drift of India away from Australia and the Cretaceous break-up of Australia and Antarctica. The northwards drift of the Seychelles-India block in the Tertiary was accommodated by the opening of the Laxmi Basin. This was followed by the eruption of the extensive Deccan flood basalts and the separation of India and the Seychelles. Crustal domains on volcanic margins can be very difficult to define due to the accretion of magmatic material. On these margins, there is much speculation on the position of the continent-ocean boundary and the timing of rifting and sea-floor spreading. The presence of magnetic anomalies indicating variable rates of seafloor spreading and 'jumps' in the axis of seafloor spreading have not as yet been satisfactorily resolved by existing plate models.

Integration of detailed geophysical and geological datasets, combined with published data will be used to produce an enhanced plate tectonic model. This will be coupled with deformable modelling of the extensional margins, incorporating stretching (β) factors and deformation trajectories to calculate the extent of crustal deformation for the main episodes of continental break-up. This will result in more accurate plate tectonic reconstructions for the determination of pre-rift geometries, palaeo-positions of the plates and exploration datasets intersected with them, to aid hydrocarbon exploration in the region.

Insights into the geometry of the Crozon fold-and-thrust belt of Central Armorica (Brittany, France)

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The extremely well preserved coastal sections of the Crozon peninsula, located in the westernmost part of the Armorican Massif of Brittany (France), display Palaeozoic sediments that rest unconformably on Late Proterozoic (Brioverian) sequences. These sediments are deformed during the Variscan orogeny by the Late Devonian to Early Carboniferous contraction-dominated 'Bretonian event'.

We present a new line-drawing which was made of the 1800 m long *Kerguillé – Lostmarch cross-section* in the southern part of the Crozon peninsula, exposing the multilayered Plougastel Formation (quartzitic sandstones and phyllites). The section shows a generally steep architecture with five large-scale, rather symmetrical upright folds and three distinct zones with a high density of centimetre to multimetre-scale, disharmonic, chevron-type folds. These small-scale chevron folds show mostly a vertical geometry similar to the larger folds. However, also N-verging asymmetrical folds are present.

In the northern part of the Crozon peninsula, the *Pointe des Capucins – Ancien Fort de la Fraternité cross-section* also exposes the Plougastel Formation. Darboux & Plusquellec (1981) describe large-scale, open, symmetric folds and centimetre to multimetre-scale, SE-verging, asymmetrical folds in this section. A new structural mapping in the northern continuation of this section, shows the presence of N-verging asymmetrical folds with an associated axial planar cleavage. We consider the presence of a local décollement between the section of Darboux & Plusquellec (1981) and its northern continuation, with N-verging folds below and SE-verging folds above the décollement.

The structure of both the northern and southern cross-section is typical in a fold-and-thrust belt with décollement levels along rheologically weaker sedimentary layers. Our new observations question the direction of the thrusting episode during the Bretonian event which is considered to be SE-verging by Ballèvre et al. (2009).

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The Quantification of Fracture Patterns

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Fractures in deformed rocks are rarely uniform or random. Fracture orientations, sizes, shapes and spatial distributions often exhibit some kind of order, or pattern. In detail, there may be relationships among the different fracture attributes e.g. small fractures dominated by one orientation, larger fractures by another. This is important because the mechanical (e.g. strength, anisotropy) and transport (e.g. fluids, heat) properties of rock depend on these fracture patterns and fracture attribute relationships. This presentation describes a methodology to quantify fracture patterns, including distributions in the fracture attributes and their spatial variation.

Software has been developed to quantify fracture patterns from 2D digital images, such as thin section micrographs, geological maps, outcrop or aerial photographs or satellite images. The software toolbox comprises a suite of MATLAB™ scripts based on published numerical methods for the analysis of fracture attributes: orientations, lengths and shapes of fracture traces are measured and their distributions quantified (e.g. mean and dispersion). A multiscale analysis based on a wavelet method is used to look for length scale transitions in the fracture attributes. Fracture trace data from multiple 2D images can be combined to derive the statistically equivalent 3D fracture orientation distribution. The software tools provide an objective and consistent methodology for quantifying fracture patterns and their variations in 2- and 3-D across a wide range of length scales.

The current focus for the application of the software is on quantifying the fracture patterns in and around fault zones. There is a large body of published work on the quantification of relatively simple joint patterns, but fault zones present a bigger, and arguably more important, challenge. The method presented is inherently scale independent, and a key task will be to analyse, interpret and integrate quantitative fracture pattern data from micro- to macro-scales.

A re-evaluation of the normally zoned Loch Doon Pluton, SW Scotland: implications for emplacement mechanisms.

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Magmatic fabrics in the late Caledonian Loch Doon granitoid provide critical clues into the evolution of this normally zoned pluton. The composition of the pluton ranges from hypersthene diorite at the margin, through quartz diorite, granodiorite, granite and cordierite microgranite at its core. Previous studies, largely based on geochemical evidence, have deduced a two-stage *in-situ* fractionation process for the generation of the compositional zones. This model is re-evaluated, based upon evidence for a planar magmatic foliation that is variably developed (strong to weak) throughout all phases of the intrusion. Results from detailed field mapping (1:10,000 over 30km²), microstructural analysis and LA-ICPMS U-Pb dating of magmatic zircon will be presented and considered in light of a new model in which the compositional zones originated from successive but distinct pulses of a melt fractionating at depth. In brief, the Loch Doon Pluton can be considered within a new model to explain: a narrow dynamic strain aureole with partially and completely discordant magmatic-host rock fabrics, indicating varying degrees of decoupling between host and plutonic rocks; vertical magmatic pipes throughout all phases, interpreted as late-stage instabilities in a crystal-rich mush along with a narrow dynamic strain aureole show a lack of in-situ inflation or ballooning of the magma chamber; and a planar magmatic foliation that is typically sub-parallel to the host rock-pluton contact and cross-cuts gradational to moderately sharp internal contacts, resulting from near-solidus grain boundary sliding and alignment of residual melt during outward and downward flow of earlier phases following intrusion of later, more evolved phases. Key relationships between magmatic faults, magmatic troughs, shear zones, folded quartz veins and conjugate fractures will also be presented. These structural data challenge the widely-accepted two-stage fractionation model for the Loch Doon Pluton, and permit consideration of an alternative emplacement model for other normally zoned Caledonian plutons.

A new mechanism for silica gel precipitation along faults caused by fluid pressure drop associated with seismogenic slip

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Based on experimental and some field-based studies several authors have proposed that silica gel (hydrated amorphous silica) layers are generated by frictional slip along seismogenic faults. The precise mechanism(s) of formation have remained somewhat enigmatic, but most studies invoke a mixture of frictional and chemical processes simultaneous with seismogenic slip. In this presentation we describe a new occurrence of ultrafine grained silica fault rocks that are hosted along a number of detachment faults developed within the Zuccale low angle normal fault on the island of Elba, Italy (see figure below). Based on the geological and microstructural observations, including very detailed EBSD measurements, we propose an alternative mechanism of formation in which the gels precipitate rapidly from supersaturated pore fluids formed due to sudden drops in fluid pressure along faults during or immediately following episodes of seismogenic slip. This mechanism may have widespread application to other examples of fault-hosted silica gels. Furthermore, given the field appearance of these layers (see figure) and the recognition of ultrafine quartz crystallites in thin section, it is possible that similar examples in other natural fault zones may have been mistakenly identified as pseudotachylytes. The implications for fault weakening will also be discussed.

Left image: *Field view of LANF detachment fault (arrowed) cutting dolomite-silica vein unit overlain by black amorphous/ultrafine silica layers up to 2cm thick.* *Right image:* *hand sample from the same locality cut parallel to transport (top to east, right) showing typical appearance of black silica layers along fault. Note that similar, slightly earlier-formed layers and lenses of similar material also occur in the hangingwall. Scale bar = 1cm.*

Seismic damage zones and their impact within thrust and fault imaging

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3D reflection seismic data provide interpreters with the ability to map structures and stratigraphic features in 3D detail to a resolution of a few tens of meters over thousands of square kilometers. Despite these great advances still great uncertainty exists as to the patterns of deformation that develop within deep water submarine thrust belts. While the superficial structure and spacing of major folds may be visible, in most cases the trajectory of thrust faults is highly conjectural. Even where seismic data are excellent, structural interpretations conventionally define thrusts by breaks and apparent offsets of seismic reflectors. Yet this may not be sufficient to identify the position of thrusts, their associated splays and the zones of damaged wall-rocks. Finally many interpretations rely on theoretical “end-member” behaviors of thrust geometry where concept as strain localization or mechanics of multilayer are for simplicity avoided and outcrop studies indicate that such descriptions are unsatisfactory. In order to fill these gaps and improve the 3D visualization of such deep water structures, in addition to the conventional mapping of reflector amplitudes, here we use seismic attributes mapping that uses variations in the amplitude and phase of the seismic wavelet and tracks these through entire data volumes. In general seismic attributes improve the signal interpretation and are calculated and applied to entire 3-D post-stack seismic volumes.
By showing clear 3D seismic example from Deep water structures and extensional system we indicate how 3D seismic image processing methods can map strain and damage through amplitude/phase properties of the seismic signal revealing narrow thrusts, plus distributed faulting and strain called "Seismic damage Zones". This is done by quantifying and delineates the short-range anomalies on the intensity of reflector amplitudes and collecting these into "disturbance geobodies”.
This seismic image processing method represents a first efficient step toward a construction of a robust technique to investigate sub-seismic strain, mapping noisy deformed zones and displacement within subsurface geology.

CGG Veritas, Taqa Bratani, project are thanked for providing access to the 3D seismic data. We thank ffA and Schlumberger for providing a copy of their software.

Insights into the Middle Pleistocene Anglian Glaciation through the magnetic analysis of diamicton

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The flow of a glacier over unconsolidated sediment can create structures that appear analogous to deformation within high strain rocks and the same techniques applied by structural geologists to unravel tectonic deformation can be applied to glaciotectonic deformation. Recently it has been suggested that one such technique, the anisotropy of magnetic susceptibility (AMS), previously used to measure strain within rocks can also be applied to understand strain within glacigenic sediments.

We have used AMS to test the hypothesis that a Mid Pleistocene aged glacigenic sequence in Sheringham, Norfolk has undergone polyphase, glaciotectonic deformation as a result of multiple phases of ice advance across the region in both subglacial and proglacial settings. Recorded in the glacial sediments are a variety of structures such as isoclinal folds, augen like bodies and rafts. However, the origin of these structures and their relationship to ice flow within the region is unclear. AMS data should reveal stretching directions that should help to determine ice flow directions through the sequence.

Presented, are preliminary results from a study using AMS and fold analysis to constrain and unravel the glaciotectonic deformation of the area. By using these techniques, strain intensity and direction can be constrained in order determine the genesis of the sediments (subglacial, proglacial, glacio-aquatic) and subsequent glaciotectonic deformation, thereby providing insights into the genesis of the structures seen and elucidating the glacial history of the area. In doing so, the study confirms the promise of the technique in providing a new, non-subjective, fast and inexpensive method of determining strain within glaciotectonically deformed sediment.

Displacement Vector Analysis: A new method for analysing cross-strike discontinuities and transverse zones

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Numerous authors have reported on geometry, kinematics and mechanics within fold-and-thrust belts. Whilst many works have dealt with palinspastic reconstructions and transport-direction-parallel balanced cross-sections, far fewer have focussed on three-dimensional architecture of fold-and-thrust belts, or examined how lateral variations in thrust architecture in different segments of thrust belts are linked via so-called 'transverse zones'. Systematic alignments on these lateral structures are suggested to be controlled by; sub-décollement basement faults, pre-thrusting cover strata deformation above basement faults, development of duplex structures/antiformal stacks, and/or along-strike variations in mechanical stratigraphy.

Transverse zone structures are greatly dependent upon pre-thrust inheritance structures of the orogenic province. Within the study areas, frontal and/or lateral inheritance structures determine structural compartmentalisation styles through the development of lateral ramps, displacement transfer faults and transverse faults. Project methodologies in this work incorporate a new method of analysing hangingwall and footwall ramps and flats through branch point/cut-off point and fault-tip point analysis. This allows three-dimensional geometries of thrust-to-stratigraphic décollement relationships and alignment with basement structures to be determined. These displacement vector analysis methodologies help to better characterise the pre-thrusting template and assess that template's capacity to control subsequent lateral thrust geometries on a variety of scales.

This new Arc Map GIS-based method has allowed three small case studies to be reinterpreted within three well-understood and comprehensively mapped thrust belts; the Achnashellach Culmination in the Moine Thrust Zone, NW Scotland; the Somiedo-Correcillas Unit of the Cantabrian Arc, northern Spain; and sections of the Anniston, Bessemer and Harpersville Transverse Zones of the Appalachian Thrust Belt, Alabama, U.S.A.

Using terrestrial laser scanning to investigate the joint pattern of a fractured carbonate reservoir analogue, Eifel, Germany

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The study area is located at the frontal part of the NE-SW striking Variscan fold-and-thrust belt, which is truncated by Mesozoic to Cenozoic NE-SW normal faults. Multiple quarries expose Variscan Carboniferous dolo- and limestones, one of them truncated by the active Sandgewand normal fault (SG-fault). In this study, we present results from a quarry located in the footwall of the Sandgewand normal fault. The rocks were affected by several fluid pulses, as displayed by multiple generations of veins. We aim to better constrain the joint sets and up-scale the distribution of joints and faults from cm- to regional scale. Results will be integrated with the fluid history as displaced by vein to better constrain the structural diagenesis in limestones.
Major joint sets strike NE-SW (parallel to the normal faults), NNE-SSW (interpreted as sub-recent anticlockwise stress rotation) and ENE-WSW (associated with transfer faults). Joints appear to rotate towards the SG-fault, suggesting a strike slip component on that fault. Joint density clearly increases towards the SG-fault.
Major faults have been observed in the Hastenrath quarry by integrating virtual planes in our laser scans. Their direction continuously changes towards the Sandgewand fault.
To prove the accuracy of the joint orientations derived from laser scans, we compared such data with traditional geological compass measurements and smartphone measurements (using the app Rock-Logger on Motorola Defy). Data derived with the mobile app have been shown to match well with traditional techniques.
Large >10 cm wide veins cut vertically through the quarry wall over several meters and are filled with calcite, galena, dolomite and sphalerite. They are only found in the vicinity (<30m) and strike parallel to the main SG-fault. Multiple sealing events were dated in a single vein at 170±4Ma, followed by a second event at 134±2Ma (e.g. Schneider et al. 2007). We now focus on the fluid inclusions to fully constrain the fluid history and integrate results with structural data.

Mid-crustal section of a crustal-scale shear zone (Malpica-Lamego Line, Variscan Orogen, NW Iberia)

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Current level of exposure in Northwestern Iberia shows the hinterland of the Variscan Orogeny. Remnants of exotic rocks and the suture of the orogen are part of allochthonous thrust sheets and are preserved in synformal klippen on top of what can be regarded in this context as the Iberian plate. The substantial migmatization of the iberian rock sequence and the large amount of simultaneous granitoid intrusions affecting this part of the orogen indicate that at a late stage of underplating the Iberian sequence was mechanically very weak. The strength of the crust back then may have resided in the upper crust, now completely eroded away.

A number of crustal-scale shear zones cut across the ensemble of allochthonous thrust sheets and Iberian rocks, most if not all have a strike subparallel to the grain of the orogen. One of them, the Malpica-Lamego Line (MLL) is the target of our work. The MLL has minimum length of 275 km and an accumulated vertical and horizontal displacement in excess of 10 km, based on the offset of the rocks units. Its tectonic activity spans an interval of several million years, from 350 Ma to around 310 Ma, thought to be split into two stages, a first episode with predominant dip-slip movement, and a subsequent strike-slip overprint. Age constraints were obtained through dating of deformed magmatic rocks in neighbouring areas.

The MLL trend parallel to the orogen is unfavourable for slip for a high angle convergence between Iberia and the microplates involved in the Variscan collision. The weakening mechanisms operating at the shear zone to allow sustained movement in such orientation must have been active for long periods of time.

We are reviewing the role of two types of fluids that are associated with the tectonic activity along the MLL: I-type granodioritic magmas and hydrothermal fluids. In terms of structures associated with the main shear zone, they are overall fundamentally ductile and plastic, but recently seams of cataclasites have been found affecting the fine-grained products of high strain deformation, such as phyllonites and mylonites.

Hinterland-propagation in the fold and thrust Loch Alsh sector of the Moine Thrust Belt, NW Scotland.

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The Moine Thrust Belt (MTB) of NW Scotland incorporates a variety of crustal-scale, thrust-dominated, and fold and thrust-dominated sectors. North of Loch Maree, the MTB is characterised by imbricate thrust stacks as exemplified by the classic Assynt region. In contrast, to the south of Loch Maree and above the Kishorn-Kinlochewe thrusts, the southern MTB is more accurately referred to as a fold and thrust belt. Large areas of overturned strata are widespread in the southern MTB but are rare north of the Loch Maree Fault – an important change in the MTB identified as the Loch Maree Transverse Zone (Kelly, M.J. et al., this conference).

New mapping and structural analysis has elucidated the architecture of the Lochalsh sector of the southern MTB. The eastern, inverted limb of the Lochalsh Syncline preserves the sheared base of the Sleat Group (Torridonian), structurally overlain by strongly sheared Lewisian Gneisses. A conglomeratic facies with undoubted gneiss clasts is locally preserved in the Torridonian rocks. Relationships across this inverted unconformity represent penetrative non-coaxial deformation within a thick, ductile, mid- to upper-crustal greenschist facies shear zone and not a discrete thrust.

East of the Lochalsh Syncline on the Lochalsh peninsula, at least six separate thrust sheets can be identified. Structurally higher thrusts truncate the underlying thrust sheet, demonstrating a hinterland propagating thrust sequence – as is evident in Tarskavaig, farther south but also structurally above the Lochalsh Syncline. These six thrust sheets alternate right-way-up and inverted successions. Inverted successions show penetrative non-coaxial deformation whereas thrust sheets carrying a right-way-up succession show far less internal deformation and locally, perfectly preserve internal depositional contacts. The Moine Thrust (s.s) truncates the lower two of these thrust sheets and truncates the axial trace of the Lochalsh Syncline on Skye. Mylonitic Moine psammite on the Moine Thrust is over-ridden by mylonitic gneiss; slivers (horses?) of mylonitic quartzite and metacarbonate rock are carried locally on this thrust.

East of the Lochalsh fold, brittle-ductile contraction in the middle to upper crust has considerably shortened successions already deformed by ductile folding and non-coxial shear in the mid- to upper crust. It is this pattern of deformation that characterises the MTB between the Kishorn-Kinlochewe thrusts and the Moine Thrust, from Lochalsh to Loch Maree. In sharp contrast the Achnashellach Culmination bulges up this fold-and-thrust system, and so demonstrates a return to foreland-propagating thrusting in the later stages of the development of the MTB (Butler et al. 2007). The (brittle) Moine Thrust then truncated both the Kishorn fold and thrust system and the Achnaschellach Culmination, indicating a final hinterland-propagating episode of movement.

Emergent Thrusts in the accretion history of the Monian (Penobscottian), outboard margin of East Avalonia.

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The island of Anglesey (Ynys Môn) records a complex and protracted history of tectonic accretion along the outboard margin of East Avalonia. The evidence for Late Neoproterozoic subduction and accretion is provided by ca. 650 Ma metamorphism in the Coedana Complex and ca. 615 Ma intrusion of the supra-subduction zone Coedana Granite through to emplacement of the Penmynydd Zone blueschist facies assemblage at around 560 Ma. During the Early Ordovician renewed (Penobscottian/ Monian) accretionary tectonics emplaced the Cambrian to Ordovician meta-sedimentary successions of the Monian Supergroup onto this composite Late Neoproterozoic margin.

That assembly is unconformably overlain by weak but variably deformed olistrostomal deposits of the Gwna Group, a molasse deposit reworking an uplifted Late Neoproterozoic shelf. The overlying unconformable and strongly asymmetric Late Arenig to Caradoc marine foreland basin of central and northwestern Anglesey records foreland migration of basinal facies and continued south- or SE-directed horizontal translation through Middle Ordovician times. Rocks of the Carmel Head Thrust Sheet represent the highest structural level in this accretionary complex, the basal thrust clearly oversteps and truncates the earlier accretionary stacking.

Silurian translation of the Carmel Head Thrust Sheet must have succeeded significant uplift and erosion of the accretionary margin. New field observations have identified locations where the basal thrust overrides molasse deposits derived from the advancing thrust sheet. The basal thrust must presumably therefore have cropped out at surface at the foot of an active fault scarp shedding detritus. Breccio-conglomerate lacking any cohesive fabric is locally preserved in the thrust footwall. Where such deposits are preserved, the thrust hanging wall is characterised by intensely cataclastic New Harbour Group phyllite that originally had reached biotite-grade. This poster illustrates these new observations, unique in the UK.

The theme of active over-riding of tectonic mollase is continued in Anglesey until the Early Devonian at least. The axially sourced fluvial Old Red Sandstone of central eastern Anglesey is over-ridden by, what is now, an outlying klippe derived from the Carmel Head Thrust Sheet.

The Effects of Macro- and Micro- Scale Deformation on Zircon and its Implications for Studies of Regional Tectonics: Examples from the Lewisian Gneiss Complex of Northwest Scotland

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Zircon is a key mineral chronometer in understanding the formation and tectonothermal evolution of the continental crust. In this study, we document the effects of macro- and micro- scale deformation on zircons from the Lewisian Gneiss Complex (LGC), a classic example of a basement gneiss complex.

Deformation at the macro-scale, in the form of high-strain discrete shear zones in Lewisian Gneisses, had heterogeneous effects on trace elements and isotopes in zircon as measured by ion microprobe. At one locality, shear zone zircons were rare, small and deformed and recorded young discordant ages and variable trace element patterns while, at another locality, shear zone zircons were large, abundant and recorded a spread of concordant ages and range of trace element patterns.

At the micro-scale, electron backscatter diffraction (EBSD) analysis highlighted five zircons from a population of ninety-nine which had intracrystalline distortion. Distortion took the form of plastic bending of the crystal lattice by distributed dislocations, or more abrupt changes in orientation due to incipient growth in a misoriented form. In both cases, the lattice distortion was found to disturb trace element and isotope concentrations relative to undistorted zircons. Ion microprobe analysis revealed that plastically deformed (distorted) zircon recorded relatively high Th/U ratios, relatively young but concordant $^{207}Pb/^{206}Pb$ ages, low Ti-thermometer temperatures and intracrystal heterogeneity in REE abundance and profile; misoriented growth zircons recorded relatively low Th/U ratios, young and very discordant $^{207}Pb/^{206}Pb$ ages, variable or high Ti-thermometer temperatures and occasional depletion in heavy REEs. The data have implications for the tectonothermal evolution of the LGC and show that EBSD analysis is important when analysing zircon populations in regional tectonic studies.

In summary, we document the effects of macro- and micro- scale deformation on trace elements and isotopes in zircons from basement gneisses. In both cases the zircons are affected heterogeneously, emphasising the importance of carefully considering the impact of different scales of deformation on zircon in studies of regional tectonics.

Fabrics produced mimetically during static metamorphism: retrogressed eclogites from the Zermatt-Saas zone, Western Alps, as an example

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Lattice preferred orientations (LPOs) are commonly interpreted to form by dislocation creep. Consequently they are used to infer deformation at the metamorphic grade at which the minerals were stable, especially if those minerals show a shape fabric. We show that LPOs can occur through mimicry of a pre-existing LPO, which impacts on their interpretation. Omphacite and glaucophane LPOs occur in eclogite facies rocks from the Zermatt-Saas Unit of the Northwest Italian Alps. Barroisite grew during retrogression at greenschist facies and has a LPO that is controlled significantly by the eclogites omphacite and glaucophane LPOs, rather than directly by deformation. We show this using spatially resolved lattice orientation data from the three key minerals, collected using Electron Backscatter Diffraction; we deploy a new technique of interphase misorientation distribution analysis. Barroisite LPO develops by mimicry of omphacite (through a particular lattice orientation relationship) and by direct topotactic and epitactic replacement of glaucophane. LPO in turn influenced anisotropic grain growth, resulting in a barroisite grain shape fabric. Our data suggest that regional retrogression during exhumation of the Zermatt Saas high pressure rocks was, in large part, static, rather than dynamic as previously interpreted. Mimetic fabrics may form during other metamorphic reactions. They must be borne in mind when interpreting direct structural observations and seismic anisotropy data in terms of deformation, in both crust and mantle.

Quantification of uncertainty in geoscience interpretation: revealing the factors that affect interpretational ability

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Abstract

Models of sub-surface geology are created from datasets that sample a limited volume of the subsurface; therefore, even with modern data collection techniques, the final model is highly dependent on the interpreter's conceptual framework. Interpreters from diverse educational backgrounds, or with experience in a range of geological settings, can come up with very different interpretations for the same data [1]. Specifically, Bond et al. (2007) showed that only 21% of the 412 interpreters sampled identified the original tectonic setting of a synthetic seismic image. The success rate rises to 35% when only 185 self-defined "experts" are considered (Bond et al. 2011). This presentation will give results from 'the Freyja project'; a research project designed to quantify the uncertainty in geoscience interpretation via the statistical analysis of 709 structural interpretations (418 experienced interpreters) of a 2D seismic image. Respondents to the survey were asked to interpret an unknown seismic image and complete a questionnaire that captured their education and geoscience experience.

In this analysis, respondents' interpretations are compared against a reference expert's interpretation (the reference interpretation may be revealed during the presentation!). The similarities between the interpretations are then statistically modelled against respondents' education, geological experience and the interpretation techniques that were used, using logistic regression. The 'effect' of individual factors (e.g. professional background, level of education and the techniques used) is quantified to determine the most and least influential factors. Key findings include that the most significant variables from the 'education and geological background' category were found to be: 'worked for an oil company', 'have a strong experience in structural geology' and 'have worked in many geological locations around the world'. However, even more significant than these 'background' factors were three interpretational techniques. Each of the techniques significantly improved the likelihood of an individual interpreter producing a more similar interpretation to the reference expert's interpretation; showing that even an inexperienced interpreter can produce a valid interpretation if they use effective techniques.

1 – Bond et al., 2007, *What do you think this is? "Conceptual uncertainty" in geoscience interpretation*, GSA Today, v17, 4-10. doi: 10.1130/GSAT01710A.1

2 – Bond et al., 2011, *What makes an expert effective at interpreting seismic images?*, Geology (in press).

Architecture of Fault Zones in Carbonates

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Understanding and unravelling the architecture of fault zones is highly problematic, even in relatively homogeneous rocks. A number of factors including lithology and stress regimes control fault architecture, often resulting in significant complexity. Faults become even more complex in carbonates due to the heterogeneous nature of these rocks. Different facies in a carbonate succession, and slight variations within each facies, will deform differently in the same stress regime. This creates highly variable fault zones, in turn making prediction of fault zone architectures in the subsurface very difficult. Fault zone architectures therefore need to be customised for individual scenarios. Recognition of fault zone architectural complexities leads to a better understanding of petrophysical properties therein and the hydraulic sealing or conduit potential of fractured reservoirs.

This study utilizes field analogues in Malta to understand the complexities of normal fault architecture in carbonates. Sedimentary logs and petrography have been used to define the shallow water carbonate facies of Malta. Small scale maps and scan lines of normal fault zones, with displacements ranging from ~20 cm up to ~95 m, have been used to build a fault architectural model. The range of fault displacements in these outcrops provides scope to understand the evolution of fault architecture and the quantification of scaling relationships.

Fault zones are often assumed to follow Caine's architectural model: a fault slip surface surrounded by a fault core, passing outwards into a damage zone with damage intensity decreasing exponentially into the protolith. However, application of this model to specific fault zones is often problematical, and the normal faults seen on Malta do not follow this generic architecture. A new model is proposed for faults with displacement >1 m, with a central fault zone flanked by two bounding faults at either side of an intense area of fracturing and deformation. Beyond the bounding faults lies a weakly deformed damage zone, and after a certain distance there is an abrupt cessation of damage into the protolith. The scaling of the Maltese fault zones and the relationships of the fault core, damage zone and protolith do not follow Caine's model. Scaling relationships and the architectures of these fault zones is complicated by the intrinsic carbonate heterogeneity. A perfect model for fault zones therefore will never exist, but better models can help us to understand the petrophysical signature of these fault zones in the subsurface.

Critical State Soil Mechanics: Can this be used to predict fault zone architectures?

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Understanding fault zone architectures through simple models has been attempted in the past, but even slight variations in lithology, tectonic regime, fluid flow, etc can create significant departures from these models. An improved understanding, leading to better predictive methods, based on more plausible fault architectures is now essential, as small variations in the architecture of fault zones can cause significant changes to their petrophysical response in the subsurface.

Scaling of fault damage around fault zones is a function of the intrinsic rock properties of the adjacent lithofacies, such as rigidity and strength. These mechanical properties may lead to differences in the timing and relative roles of strain hardening and strain softening, ultimately causing variations in the thickness of fault cores and damage zones. Although this has previously been suggested (Ben Zion and Sammis 2003; Van Gent 2009), there have been few attempts at a rigorous quantification of such lithological control on fault damage.

Using data collected from an ongoing study from normal faulted carbonates in Malta, a potential method for predicting fault architectures has been identified. Examination of deformation mechanisms and porosity, and inferences about the strength of the rocks, will be used to create different scenarios for a critical state soil mechanics (CSSM) analysis of two different carbonate facies: mud- and grain dominated. These two carbonate facies accommodate stress and strain by very different deformation mechanisms, due to their differing intact strengths, sizes of clasts/grains and their original porosities. The use of deformation mechanisms and porosity can help to identify the timing of the transition from strain hardening to strain softening, i.e. providing a time frame for when the critical state line is breached for each of the facies. Timing (and ultimately displacement) for this transition can lead to recognition of how much deformation the rocks have been through before localization of deformation occurs, leading to the cessation of fault zone growth. CSSM can indicate the relative length of time spent strain hardening, and therefore could lead to a quantification of the width of the fault zone.

3D Structural Model Building and Fold Construction using a Digital Dip Isogon Construction Method: The Mt. Lykaion (Greece) Sanctuary of Zeus Case Study

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During the past several years an iterative, year-to-year program of detailed field-based geological mapping followed by 3D model building has resulted in a cohesive representation of the structural geology of the Sanctuary of Zeus, Mt. Lykaion, in the Peloponnese, Greece. The fundamental bedrock structure is one of large-scale folding and thrust faulting, overprinted by more modest superimposed normal faulting. For example, one of the major anticlines, located directly beneath a very low-dipping regional thrust fault, is symmetrical and upright in its deepest exposures, transforming upward into an overturned fold. The transition is sharp, taking place above a bedding-parallel detachment fault. Two stratigraphic formations with contrasting rheologies are affected by this folding. The rheological differences become manifest in changes in layer thickness from limbs to hinge zones. In particular, one of the formations favored the development of Ramsay Class 1b folds; the other by Class 1c folds.

To achieve a structural compatibility of the 3D model with the fundamental map data (contacts, bedding-orientation data, fold-orientation attributes) we used a digital Dip Isogon Construction Tool in Midland Valley's MOVE software allowing subtle distinctions in strain attributes from formation to formation to be made. This construction method allows all folds in the Ramsay classification to be modeled, starting from outcrop dip data, or from a template bed. This results in significant improvements in modeling fold styles than can be achieved with a toolkit that allows only parallel and similar fold construction.

Working in a 3D digital environment has allowed integration of field data (bedding measurements, geological contacts, fold axial traces and landscape images displaying the expression of bedding and structure) with remote sensing data (DEM and aerial photographs). Of particular value is the ability to access, display and integrate the full range of heritage and new geological data within the same digital platform. Simultaneous visualisation and real-time update of work in progress in map, section and 3D views in an iterative approach helps establish an accurate portrayal of all of the structures and contacts. As an added benefit beyond structural geologic analysis, the visualization products lend themselves to an important aspect of the underlying geoarchaeological objectives: communicating geology to non-geologists, e.g., classicists and archaeologists.

Channel flow extrusion model to constrain viscosity and Prandtl number of the Higher Himalayan Shear Zone

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The channel flow extrusion of the Higher Himalayan Shear Zone (HHSZ) involved a top-to-SW simple shear in combination with a pressure gradient induced flow against gravity. Presuming a Newtonian incompressible rheology of the HHSZ with parallel inclined boundaries- the Main Central Thrust-Lower (MCT_L) and the South Tibetan Detachment System-Upper ($STDS_U$), the viscosity of the HHSZ along the entire Himalayan chain within India, Nepal and Bhutan is estimated to vary between ~ 10^{16}-10^{23} Pa s, and its Prandtl number within ~ 10^{21}-10^{28}. The parameters specifically for the HHSZ in the Sutlej section (India) are calculated to be ~10^{17}-10^{23} Pa s and ~ 10^{22}-10^{28}. These estimates utilized ranges of known thickness (6-58 km) of the HHSZ, and that of its top sub-zone of reverse ductile shear ($STDS_U$: 0.35-9.4 km), total rate of slip of its two boundaries (0.7-0.69 mm y^{-1}), pressure gradient (0.2-6 kb km^{-1}), density (2.2-3.1 g cm^{-3}) and thermal diffusivity (0.5×10^{-6}-2.1×10^{-6} m s^{-2}) along the studied orogenic trend. The deduced magnitudes are in conformity with a strong Tibetan mid-crust, and range within those for its constituent main rock types, partly for the superstructure and partly for the infrastructure. The estimated magnitude of viscosity will help to build dynamically-scaled analogue models of the evolution of the Himalaya.

Crystallization-force experiments in porous microreactors

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The objective of this work is the development and first experiments in a microporous flow-through reaction cell, examining the nucleation and crystallization of analogue material (alum) in porous media. Three different micro-models are used for this purpose: Two porous microreactors using glass spheres but different transport mechanisms (diffusion and advection) and another model of non-reactive micro-pores.

With such models we simulate the variation of pore clogging in bedded sedimentary rock and examine the impact of “force of crystallization” on the development of pores. The quantification of pore clogging is relevant to diagenetic studies and enhanced oil recovery, while “force of crystallization” is related to a lot of processes, e.g. fracture- & vein formation.

An analogue micro-model of a porous medium is created by selective laser-induced etching. By using this special technique, we design a 3D porespace with pore sizes of down to 10 µm. Before starting fluid flow of a supersaturated solution, randomly distributed nuclei of seed crystals are generated within the transparent cell by spontaneous nucleation. In another porous microreactor, crystallization was controlled just by diffusion.

Homogeneous nucleation is observed throughout the diffusion experiments. Emphasis was laid on the impact of pore size on crystallisation and solubility. Pore-size controlled solubility (PCS, see Emmanuel & Ague, 2009) could be observed in some of these laboratory experiments, as it is observed in the field (Putnis & Mauthe, 2001), although full cementation was expected due to “off scale” fluid supersaturations in the lab compared to those nature.

Quaternary tectonic uplift of the Kyrenia Range, northern Cyprus: preliminary field results and objectives

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The Kyrenia Range experienced surface uplift from near sea level in the Late Pliocene to ~1000m at present. A flight of Quaternary terraces is exposed along the northern and southern flanks of the range, becoming successively younger with altitude and distance from the central range. The highest terrace (Karka), up to 365 m above sea level (asl), fringes the mainly Mesozoic-Early Cenozoic carbonate rock core of the central Kyrenia Range. This terrace is dominated by poorly sorted, non-marine scree-type breccia and mass-flow deposits, with clasts of mainly Mesozoic limestone/dolomite and some Paleogene pelagic carbonate/volcanic rocks. The next terrace below, the Arapköy (Klepini) Terrace ~285 m asl, exhibits the earliest shallow-marine calcarenite, passing upwards and laterally into aeolianite and then into channelised conglomerates and braided stream deposits. Below this, the Çatalköy (Ayios Epitikos) Terrace (~50-70 m asl) shows a comparable order and range of facies. Beneath this, the prominent Eutyrrhenian Girne (Kyrenia) Terrace (~20m asl) is dominated by littoral calcarenite, passing upwards into cross-bedded aeolianite. Finally, just above sea level is a thin Neotyrrhenian terrace composed of littoral calcarenite. All of the shallow-marine calcarenites are dominated by bioclastic debris, including bivalves, calcareous algae, rhodoliths and solitary corals. An important objective is to date the terraces and correlate them with their non-marine equivalents exposed along the southern margin of the range. Dating can be achieved using a combination of palaeomagnetism (for >750ka terraces; i.e. pre first magnetic reversal), optically stimulated luminescence (e.g. <250 ka aeolianites) and U-series dating of well-preserved corals in younger terraces.

Geomorphology can be used to shed light on the relative rates of uplift and any tilting through time. For example, GIS and digital elevation modelling can help quantify terrace morphology and indicate any structural influences on uplift. The analysis of the distribution, altitude and geometry of fluvial incision features (e.g. knick points) can indicate phases of increased uplift or erosion. The combined information to be obtained aims to test alternative models of crustal uplift including localised fault-controlled uplift (along a large-scale strike-slip 'tectonic escape' zone) versus deep-seated regional uplift (related to break-off of the oceanic leading edge of the African plate).

Sensitivity of elastic waves to hydro-mechanical variations of fault zones: an experimental approach

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In the last 20 years, active seismic surveys (Vertical Seismic Profiling - VSP) carried out in deep scientific boreholes drilled in crystalline rocks provided valuable structural data: fracture zones and faults have been identified in the vicinity of the SG3, KTB and Soultz scientific wells (located respectively in the Kola Peninsula, in Germany and in France) that would have otherwise been difficult to image. Although some of these structures have been successfully mapped in 3D, questions remain open about the elastic behaviour of fault zones: in some cases, the thickness of these structures is much smaller than the wavelength of the seismic waves they can reflect. In addition, propagation mode conversions are observed, such as *P–S* converted reflections, on structures exhibiting a relative high hydraulic conductivity. From these field observations, the elastic response of a fault seems to be strongly related to its porosity and the fluid pressure conditions, both of them implying a mechanical defect. Nevertheless, this elastic behaviour has never been satisfactorily explained by theoretical works and subsequent modelling.

In order to investigate the seismic properties of these fractures and faults, we are developing an experimental approach at the laboratory scale. Synthetic faults and fractures are replicated by clay-filled saw cuts in samples of fine-grained isotropic granite. These samples are submitted to confining pressures up to 200 MPa in order to reproduce on field deep conditions. Our hydrostatic apparatus is equipped with microseismic sources and sensors, to allow monitoring of the reflectivity and the transmissivity of elastic waves on the artificial fault zone. The main point of our approach consists in making the pore pressure vary so as to inflate/deflate the fault zone, implying variations of the mechanical coupling of both fault-compartments to which the seismic waves are supposed to be sensitive. The first results will be presented, illustrating the effects of the pore pressure, the nature of the fault zone (clay, clay + quartz grains...), and the incidence angle.

Key words:

Fault zone, hydro-mechanical conditions, seismic waves, faults activity monitoring, fractured reservoirs.

Intrusive peridotites and granites exhumed on Seram and Ambon, eastern Indonesia during Banda Arc subduction rollback

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The Banda region of eastern Indonesia, which accommodates the relative motions of the Eurasian, Australian, and Pacific plates, has a complex tectonic configuration. Seram and Ambon, islands of the northern limb of the Banda Arc, include granites and dacites as young as 3 Ma which are associated with regional metamorphic rocks and peridotites. The island has been interpreted as a fold-and-thrust belt incorporating northward-obducted ophiolites intruded by granites generated by anatexis within a metamorphic sole. However, new mapping and recently-discovered field-relations question this interpretation.

There is no evidence for the peridotites belonging to an ophiolite and other components of an ophiolite are absent. 3 Ma granites characterised by abundant cordierite and garnet, and numerous cordierite+spinel gneissose restites, are in contact with the peridotites and crystallised at ~6 kbar (~20 km depth). Eruptive cordierite+garnet dacites ('ambonites') are widespread on Ambon and have a similar ~3 Ma age. There are many examples of peridotite intrusion into the granites. The peridotites and granites seem to comprise a single tectonic unit exhumed along low-angle NNE-dipping detachments, not obducted by SSW-dipping thrusts as previously thought. Mica schists of the hanging wall show contact metamorphism with slight anatexis adjacent to the peridotite contact. Seram's central fault zone, which strikes parallel to these low-angle peridotite detachments, incorporates thin slivers of peridotite and may have been active at a similar time. North of the central fault zone in the Kobipoto Complex, boulders of similar cordierite-granites as well as HP garnet+pyroxene granulites are found in association with peridotites and were probably exhumed in a similar manner to those of west Seram.

We suggest these observations support new geophysical evidence and plate reconstructions proposing major extension in the Seram region driven by subduction rollback of the Banda Arc. Based on the field relations, a possible explanation is: (1) lithospheric delamination, driven by rollback, caused intrusion of mantle peridotites into the lower crust; (2) gneisses adjacent to peridotite intrusions melted to form granitic melts which erupted as ambonites; (3) peridotite and granite were exhumed together along NNE-dipping low-angle detachments during crustal extension; and (4) juxtaposition of hot peridotite against the mid/upper crust resulted in contact metamorphism and anatexis close to the contact. This investigation is still very much a work-in-progress, with further geochronology, thermobarometry, and Ar-Ar thermochronology scheduled to test and quantify the above working hypothesis.

Constraints on 3D fault and fracture distribution in basalt-clastic sequences from Terrestrial Laser Scan (LIDAR) datasets: Faroe Islands

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Hydrocarbon reservoirs commonly contain an array of fine-scale structures that cannot be resolved using seismic imaging or well log analysis, such as, polyphase fracture networks, small displacement faults and small-scale fault damage zones. The properties of related fault rocks, as well as fracture distribution, connectivity and density, are important as they each play a significant role in controlling fluid flow within the prospective reservoir. In order to maximise recovery and enhance production, it is essential to understand the geometry and distribution of these structures in 3D. Here we use a LIDAR-obtained 3D, photo-realistic virtual outcrop of a 4m displacement strike-slip fault zone in basaltic lavas and volcaniclastic sediments from the Faroe Islands, to understand 3D fault and fracture distribution. Images were draped onto the high resolution LIDAR point data and interpreted using field observations. Fault, fracture and vein traces were converted into polylines using RiSCAN. A structural modelling workflow in GOCAD was then used to produce a representative fracture network model from these polylines. Despite the model being geologically sound, it is apparent that there is some uncertainty with respect to the displacement and 3D geometry of the fractures. To resolve this, we have investigated a range of aspect ratios for the fractures, to gain an insight into the fracture density and relative connectivity. Continuing work will integrate detailed field analyses, including 1D and 2D transects, structural logging and mapping as well as microstructural characterisation from collected samples, in order to understand the complex nature of fracture networks in basaltic and volcaniclastic rocks. Sub-seismic fracture distribution modelling will be used to determine connectivity within the prospective reservoir. Additional constraints from field and experimental data will be integrated into a fluid flow simulation study, which can be incorporated into ongoing exploration offshore in the Faroe-Shetland Basin.

Development of Crestal Collapse Structures above Dissolving Salt Anticlines: Application to Seismic Interpretation within Salt-Controlled Basins

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Salt-controlled basins represent some of the principal hydrocarbon provinces of the world. Their potential, and their exploitation, are governed by complex 3D interactions between host sediments and structural geometries related to salt mobility, which are often unresolvable on seismic. Consequently, much of the complexity of salt-controlled regimes is often overlooked. In the UK Central North Sea, structures related to the dissolution, and subsequent crestal collapse, of salt walls provide ideal geometries for hydrocarbon entrapment, but are poorly imaged on seismic. An in-depth understanding of the structural styles that control salt wall collapse, particularly at the 'sub-seismic' scale, is essential in order that meaningful interpretations can be made based on seismic data.

The excellent exposure and preservation of a number of collapsed salt walls and related structures within the northern Paradox Basin, SE Utah, USA, provides an ideal opportunity to investigate the structural development of crestal collapse structures at field scale. Observations based on these exposed examples can then be utilised as a tool to improve interpretations of sub-surface examples made from seismic data. Here, we present a series of 3D numerical models, based on detailed structural mapping and satellite image interpretation, of some of the key structural styles that facilitate crestal collapse of the Paradox Basin salt walls, and compare their geometry and development to equivalent structures from the U.K. Central North Sea.

Initial results from the Paradox Basin show that crestal collapse of salt walls is controlled primarily through development of a single listric fault, with an associated hanging-wall rollover anticline. Hanging-wall fault systems are highly complex, comprising numerous syn- and antithetic normal faults with an en-echelon arrangement, showing displacements typically in the range of 10—50 metres. Faults commonly show rapid changes in displacement along strike, resulting in complex accommodation zone geometries and numerous small closed structures. Equivalent collapse structures interpreted from 3D seismic data from the UK Central North Sea show large-scale controlling faults that are strikingly similar to those exposed in the northern Paradox Basin, thus supporting the concept of applying field-based models to subsurface interpretations.

The field-based models presented here provide the basis for development of a set of idealised summary models that represent the range of structural styles present above collapsed salt walls, and constitute the early stages of development of one of the first detailed frameworks to guide interpretation of seismic data in salt-controlled basins.

The Eurekan Orogeny: the tectonic culmination of the Sverdrup Basin, Canadian Arctic Islands

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Sedimentation in the Carboniferous to end-Cretaceous Sverdrup Basin ceased with the onset of the end-Cretaceous to Paleogene Eurekan Orogeny. Uncertainties about the extent of Eurekan structures, and the intensity, timing and geodynamic cause of Eurekan deformation pose a significant risk for hydrocarbon exploration in the western Arctic. They are also an obstacle to resolving many of the older tectonic events in the region (e.g. the late Devonian Ellesmerian Orogeny).

Over several years, CASP geologists have carried out fieldwork in the Canadian Arctic Islands, focussing on the Carboniferous to end-Cretaceous Sverdrup Basin succession and more recently on the Cambrian to end-Devonian Franklinian succession. Several major Eurekan structures and the effects of Eurekan deformation in the Sverdrup Basin succession have been studied. Eurekan structures have also been compared with the older polydeformed Franklinian succession.

A review of the Eurekan Orogeny is currently underway and aims: 1) to distinguish the effects of the Eurekan Orogeny from older tectonic events, 2) to highlight the specific questions that remain about this important but enigmatic tectonic event, and 3) to allow us to target field sites where we can address these issues.

Tectonics, structure, and hydrocarbon potential of the Mexican Ridges fold belt, western Gulf of Mexico.

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The western Gulf of Mexico basin is a passive margin where Tertiary gravity spreading processes resulted in a regional extensional-contractional linked system. The extensional movement associated with growth faulting on the coastal plain, continental shelf and upper continental slope is accommodated downdip by compression on a Paleogene regional basal detachment. As a result, the contractional growth structures of the Mexican Ridges evolve during the Neogene in the deep water sector covering - the western slope of the basin in front of the states of Tamaulipas and Veracruz, Mexico.

The Mexican Ridges fold belt is characterised by symmetric and asymmetric detachment folds and break-thrust detachment folds, with some of these folds related to back-thrusts. Most of the contractional folds are multi-detachment structures. The basal detachment level consists of overpressured shales of the upper Eocene. An additional detachment level has been identified on the Oligocene-Miocene unit.

Although structural styles and detachments have been interpreted along the entire contractional system, we use an up-dated regional tectonic-structural map and depth-converted regional and local cross-sections from the north and south province to: 1) illustrate notable differences, in the trend trajectories and geometry of growth structures, 2) determinate age and phases of deformation using a detailed interpretation of pre- and syn-tectonic strata, and 3) propose two different tectonic evolution models between the South and North Mexican Ridges.

This structural analysis is useful to characterize structural styles and potential hydrocarbon traps, especially at the North Mexican Ridges fold belt, an area where extensional and contractional tectonics interact with salt and shale tectonics to produce a more complex Tertiary evolution. . In addition, we suggest that this interaction enhances the active petroleum systems. This includes migration and trapping of hydrocarbons in the sedimentary column resulting in seismic anomalies, overpressured structures, gas chimneys, and sea floor seeps that require detailed evaluation.

Implications of petrostructural analysis for the tectonic evolution of the Neoproterozoic Tasriwine ophiolite (Anti-Atlas, Morocco)

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We present the results of a field, structural and petrographical study of the *c.* 760 Ma [1] Neoproterozoic ophiolite of Tasriwine, located in the Anti-Atlas Orogen of Morocco. This ophiolitic sequence is composed successively of serpentinites, talc-serpentine schists (metaharzburgites), pegmatitic amphibolites (metapyroxenites), porphyroclastic to mylonitic amphibolites (metagabbros), meta-dolerites, intrusive plagiogranites and few metabasalts.
Equilibrium temperatures of hornblende-plagioclases assemblages range from 430° to 730°C (± 40°C) and from 350° to 600°C for chlorites, at lowpressure conditions (~2-3 kbar). Presence of specific almandineamphibole-plagioclase assemblages argue for localised metamorphism acquired under low geothermal gradient (660°C, 9 kbar).
Foliation azimuths trend from N80° to N140° and two main populations of stretching lineations are observed. Thus, we distinct a first southward movement marked by foliated structures, recumbent folds and down-dip lineations (D1a). Contraction of the nappe stack leads to the formation of upright tight folds with horizontal axis and a generalised verticalisation of the structures (D1b). Late stage deformation is marked by asymmetric upright isoclinal folds with vertical axis, horizontal to moderately dipping lineations (D2), asymmetric porphyroclasts and C-S shear bands formed in a globally sinistral transpressive regime. The ophiolite has thus accommodated pre- to syn-collision obduction by horizontal displacement of thrust sheets toward the SW (D1a); syn-collision crushing (D1b) marked by upright structures. The continuation of the post-collision convergence related to the sliding of the northern Avalonia-related blocks along the northern margin of the West African craton led to a sinistral transpressive regime accompanied by the formation of intense shear bands [2] and reorganization of the structures. Calculated PT conditions show that the ophiolite has registered both low-P metamorphism (oceanic or orogenic) and LT-MP recrystallisation. The latter is an evidence for partial subduction and extrusion of some oceanic thrust slices.

[1] Samson *et al.*, 2004. *Precambrian Research*, vol. 135 (1-2) pp. 133-147
[2] Ennih *et al.*, 2001. *Journal of African Earth Sciences*, vol. 32(4) pp.677-693

Seismic imaging of salt diapir flanks constrained by outcrop data

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A large amount of hydrocarbon accumulations worldwide are trapped in salt-related structures. Recent and ongoing improvements in the seismic imaging of these structures must be coupled to improvements in our ability to interpret these images. In this study, seismic modelling is used to incorporate high resolution outcrop information into the interpretation of lower resolution seismic images, making these images more applicable to a range of exploration, development and production problems.

The nature of the overburden determines the steepness and degree of fracturing in the rocks adjacent to a salt diapir. These deformed flank zones are of great interest for hydrocarbon exploration, as they create structural traps and influence reservoir architecture varying as a function of distance from the salt body. However, these flank zones are also very difficult to image seismically. Salt flanks result in poorly illuminated areas on seismic images mainly due to their steep dips, while the large velocity contrast between the salt and the host rocks increases uncertainty in the velocity model, which in turn leads to inaccurate seismic images. In particular, when potential trap structures are seismically illuminated from different directions, inaccuracies in the velocity model can produce unrealistic geometries.

The main aims of this study are to investigate the geometry and petrophysical properties of structures adjacent to salt flanks at outcrop scale and to model their seismic response. Better constraints for reservoir geometry and rock properties can be derived from outcrop-based geological models. This information will be used to formulate upscaling strategies that realistically account for the effects of heterogeneity and anisotropy in structurally complex salt margins. Outcrop analogue mapping and sampling are to be combined with petrophysical characterisation in order to construct a detailed 3D geological framework model encapsulating these heterogeneities and anisotropies. Seismic forward modelling based on these geological framework models will be performed and compared with recorded seismic data. Initial results from synthetic modelling provide insights into generating closer matching between seismic responses and the geometries and properties we can measure in the field.

Composition and origin of exotic, fault-related intrusions, Karakoram Fault, Ladakh

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The Karakoram Fault is a dextral strike slip fault that cuts across the Eastern Karakoram Range in Ladakh, NW India. Pseudotachylyte fault rocks have been documented to occur in the Nubra Valley (Phillips & Searle, 2007) which follows the surface trace of the Karakoram Fault. The suspected pseudotachylytes are found within one of several minor fault strands which are thought to be the surface expression of the main fault; these minor faults deform a range of lithologies including volcano-sedimentary rocks and granitoids that exhibit mylonites, protomylonites, cataclasites and fault gouge.

Samples of the supposed pseudotachylyte veins were collected and analysed using optical microscopy, SEM (Scanning Electron Microscopy) techniques, EBSD (Electron Back Scatter Diffraction) and Electron Microprobe analysis. Analysis has shown the veins are almost pure tourmaline and not pseudotachylytes. Evidence suggests the tourmaline was emplaced into the host rock by boron-bearing fluids that used fault-generated fractures to migrate from a hydrothermal system at a deeper crustal level. Secondary quartz, also found within the veins, is likely to have crystallised from the same hydrothermal fluids as the tourmaline. The presence of multiple phases of fluids in the fault zone is likely to have had an effect on fault slip behaviour by altering the stress states across the fault plane, altering mineral phases to weaken or strengthen the fault, changing the permeability across the fault zone and possibly controlling the slip regime whether it is steady-state or stick-slip.

Partitioning of lithosphere stretching and thinning at continental rifted margins: Norwegian margin study

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The Norwegian rifted continental margin was formed by Mesozoic rifting of the North Atlantic and subsequent breakup at 55 Ma. The continental margin reveals pre-breakup deformation of the lithosphere during the Triassic, Jurassic and Cretaceous Periods. This study examines the Lofoten, Vøring and Møre segments of the Norwegian rifted margin in order to understand better the evolution of this margin. Interpreted seismic crustal profiles have been analysed to determine the amount of continental lithospheric thinning and upper crustal extension from the Triassic to present day. The structure of the continental crust, the amount of crustal thinning, and the position of the ocean continent transition (OCT) and the continent ocean boundary (COB) have been addressed. This study shows that the Norwegian rifted margin experienced breakup depth-dependent lithospheric stretching and thinning, where whole lithosphere stretching and thinning exceeds that of the upper crust. Earlier (pre-breakup) lithospheric deformation during the Triassic, Jurassic and Early Cretaceous rifting is shown to be depth-uniform in nature, leading to intra-continental rift basin formation. The non-coaxial superposition of lithospheric thinning from the earlier intra-continental rift events with Early Tertiary breakup thinning has led to a complex and laterally varying distribution of thinned continental lithosphere. It is important to understand the structure and rifting history in order to partition the stretching and thinning of the Norwegian continental margin. Application of these methods allows better predictions of subsidence and heat flow history for the Norwegian and other rifted margins.

Determining Relay Zone Linkage Geometry for Faults Close to Seismic Resolution

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Determining whether overlapping fault segments transfer displacement via a hard or soft linked relay zone is often difficult in seismic data where faults have displacements close to, or below, the limits of resolution. Where hard linkage occurs such faults may act as barriers or baffles to fluid flow in the subsurface, hence impacting on hydrocarbon reservoir performance. We use outcrop, LIDAR and 3D seismic data at a range of scales to develop empirical relationships for predicting fault linkage geometry within relay zones using parameters which can be readily obtained from seismic data.