

## **Welcome to Leeds**

For 2013, the Tectonic Studies Group Annual Meeting has been convened by structural geologists based at the University of Leeds:

Richard Phillips  
Geoff Lloyd  
Douglas Paton  
Taija Torvela

The meeting has been made possible through the generous support of:

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# **Tectonic Studies Group Annual Meeting 2013**

## ***Technical Programme***

Many thanks to the sponsors of TSG2013:  
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### **DAY 1 – THURSDAY 3<sup>rd</sup> JANUARY**

10:00 Registration and poster/talk set-up

10:45 Welcome

#### **Session 1: Fault Zone Processes I**

Chair: Dave Healy

11:00-12:45

#### **Keynote Lecture: Geological constraints on fault dynamic weakening mechanisms from natural slip surfaces in carbonate faults**

Holdsworth, RE; De Paola, N; Agosta, F; Balsamo, F; Bullock, R; Dempsey, E; Faoro, I; Storti, F  
11:00-11:30

#### **Fault weakening across the frictional-viscous transition zone, Karakoram Fault Zone, NW Himalaya**

Wallis, D; Phillips, RJ; Lloyd, GE

#### **Reduction of friction on faults by weak-phase smearing**

Hackston, A; Rutter, E; Yeatman, E; Brodie, K; Mecklenburgh, J

#### **Reactive transport modeling of fault-controlled fluid flow during growth of a normal fault network, Jebel Akhdar Dome, Oman.**

Stenhouse, P; Cox, SF; Virgo, S; Arndt, M; Urai, JL

#### **Understanding the evolution of ultrasonic velocities in carbonate hosted normal fault zones**

Haines, TJ; Michie, EAH; Neilson, JE; Healy, D

#### **Modelling a strike-slip fault system affecting porous carbonates in Favignana Island (Sicily, southern Italy)**

Cilona, A; Tondi, E; Agosta, F; Johnson, G; Shackleton, R

#### **Poster session and lunch**

12:45-13:30

#### **Session 2: Fault Zone Processes II**

Chair: Bob Holdsworth

13:30-14:45

#### **Influence of fault rock foliation on fault zone permeability: The case of deeply buried arkosic sandstones (Grès d'Annot, SE France)**

Cavailhes, T; Labaume, P; Sizun, JP; Chauvet, A; Soliva, R; Buatier, M; Charpentier, D; Travé, A; Gout, C

**Geometric analysis and scaling relations of lozenges and lenses in deformation bands and normal faults**

Awdal, A; Healy, D; Alsop, I

**Effects of petrophysical anisotropy on fault stability in porous sandstones**

Farrell, N; Healy, D; Taylor, C

**Discrete element modelling of the formation of layer-parallel veins in mechanically anisotropic multilayer sequences**

Torremans, K; Muchez, P; Sintubin, M

**The influence of open fracture anisotropy on CO<sub>2</sub> movement in geological storage complexes**

Bond, CE; Wightman, R; Ringrose, PS

**Poster session and refreshments**

14:45-15:15

**Session 3: Basin Analysis I**

Chair: Douglas Paton

15:15-16:15

**Geometry and kinematics of accommodation zones related to salt wall collapse.**

Randles, T; Clarke, S

**Growth History of Fault-Propagation Folds and Interaction with Seabed Channels in the Toe-Thrust Region of the Deepwater Niger Delta**

Jolly BA; Lonergan, L; Whittaker, AC

**Quantifying the timing and magnitude of fault reactivation in the northern North Sea**

Bell, RE; Jackson, CAL; Whipp, PS; Clements, B

**Recent Findings in the Geodynamic Evolution of the Equatorial Atlantic and their implications on Petroleum Systems**

Hill, C; Sagi, D; Masterton, S; Webb, P

**Poster session, with refreshments**

16:15-17:30

**BBC Public Lecture: Prof Iain Stewart**

‘The Story of the Continents’

Rupert Beckett Lecture Theatre, University of Leeds

7:30-8:30 (refreshments available from 7pm)

## **DAY 2 – FRIDAY 4<sup>th</sup> JANUARY**

### **Session 4: Structural Geology – General I**

Chair: Mark Allen

09:30-10:45

#### **Deformation mechanisms accommodating igneous sill emplacement in the Irish sector of the Rockall Basin**

Magee, C; Jackson, CAL

#### **Inverted crater in the Nafud Basin: impact structure localises igneous tectonics**

Stewart, SA; Neville, AS; Cook, D; Afifi, AM; Muzaiyen, E

#### **The intrusion ‘space-problem’: a case study of accommodation and deformation structures associated with the emplacement of the Maiden Creek satellite intrusion, Henry Mountains Utah**

Wilson, PIR; McCaffrey KJW; Holdsworth, RE; Murphy, PJ

#### **Linear volcanic segments in the Sunda Arc, Indonesia, identified using the Hough Transform**

Pacey, A; Macpherson, CG; McCaffrey, KJ

#### **Apparent structural movement paths (*asmops*), a 3D treatment of 3D shear zones**

Talbot, CJ

#### **Poster session and refreshments**

10:45-11:15

### **Session 5: Neotectonics & Active Fault Processes I**

Chair: Richard Phillips

11:15-12:45

#### **Keynote Lecture: Earthquake Cycle Deformation and the Strength of Continental Lithosphere**

Wright, TJ; Elliott, J; Ryder, I; Wang, H

11:15-11:45

#### **Interseismic strain accumulation across strike-slip faults in the Middle East**

Walters, RJ; Elliott, JE; Li, Z; Parsons, B; Wright, TJ

#### **Tectonic Studies Group Annual Business Meeting**

12:00-12:45

#### **Poster session and lunch**

12:45-13:30

## **Session 6: Neotectonics & Active Fault Processes II**

Chair: Tim Wright

13:30-15:15

### **Deformation processes along continental transform faults: the southern Dead Sea Fault System, Israel**

Evans, S; Holdsworth, RE; Marco, S; De Paola, N; Weinberger, R

### **Observations of fault linkage and growth during the 2005 Dabbahu rifting episode from high-resolution airborne LiDAR and InSAR data.**

Hofmann, B; Wright, TJ; Paton, D; Rowland, J; Vye-Brown, C

### **Comparing Long and Short Term Deformation in the Krafla Fissure System, NE Iceland, using LiDAR, InSAR and GPS**

Bramham, E; Wright, TJ; Paton, D; Sigmundsson, F; Pagli, C

### **Lithological controls on the frictional behavior of a seismically active, upper crustal carbonate fault**

Bullock, R; De Paola, N; Holdsworth, RE

### **Earthquake focal mechanisms in anisotropic rocks and minerals: a cautionary tale**

Healy, D; Dempsey, E; Timms, N; Prior, D

### **Investigating fault friction by re-examining earthquake nodal plane dips**

Middleton, T; Copley, A

### **Characterisation of active faulting in the Mongolian Altay Mountains based on previously unknown ancient earthquake surface ruptures**

Gregory, LC; Walker, RT; Nissen, E; Mac Niocaill, C; Gantulga, B

### **Poster session and refreshments**

15:15-15:45

## **Session 7: Regional Tectonics I**

Chair: Ken McCaffrey

15:45-17:00

### **Orogenic plateau growth: expansion of the Turkish-Iranian plateau across the Zagros fold-and-thrust belt**

Allen, MB; Saville, C; Blanc, EJP; Talebian, M; Nissen, E

### **How to restore the Anatolian continent and its suture zones?**

Robertson, A; Parlak, O; Ustaömer, T

### **Where the Caledonides overlaps the Grenville: The Grenvillian Glenelg Inlier as an allochthonous pip within the Moine fold-nappe complex, Scottish Caledonides**

Krabbendam, M; Ramsay, JG; Leslie, AG; Tanner, PWG; Dietrich, D; Goodenough, KM

### **Hyperextension, rifted margin geometry and its incorporation into mountain belts: Insights from the western Alps**

Butler, RWH

**The Carboneras Fault Zone, SE Spain: part of a stretching transform fault system**

Rutter, EH; Faulkner, DR; Burgess, R

**Poster session, with refreshments**

17:00-18:00

**Conference Dinner (Queens Hotel)**

19:00 onwards

**DAY 3 – SATURDAY 5<sup>th</sup> JANUARY**

**Session 8: Basin Analysis II**

Chair: Clare Bond

09:30-10:45

**Has the western Greenland continental margin experienced depth-dependent stretching?**

Alsulami, S; Paton, D; Cornwell, D; Stuart, G

**The influence of Caledonian structures on Late Jurassic faulting offshore western Norway: new insights from 3D seismic reflection data**

Reeve, MT; Bell, RE; Jackson, CAL

**A Workflow for the Application of Critical Stress Analysis with Elastic Dislocation Modelling for Developing a Framework to Consider Likely Effects of Stress Anisotropy on Permeability within a Reservoir.**

Oldfield, S

**Relationships between tectonic fractures and cliffs morphologies: examples along chalk coast in France (Normandy, Picardy, Boulonnais)**

Vandycke, S; Duperret, A; Colbeaux, JP

**Pre-Arenig accretion history on the outboard (Monian) margin of East Avalonia, Anglesey, NW Wales.**

Leslie, AG; Schofield, DI; Wilby, PR; Burt, CE; Leslie, AB

**Poster session and refreshments**

10:45-11:15

**Session 9: Microstructural Analysis**

Chair: Ernie Rutter

11:15-12:45

**Keynote Lecture: Quartz fabric-based deformation thermometry: examples of its application, relationships to petrology-based PT paths, and potential problems**

Law, R; Waters, D; Morgan, S; Stahr, D; Francis, M; Ashley, K; Kronenberg, A; Thomas, J; Mazza, S; Heaverlo, N

11:15-11:45

**Quartz geothermometry and geospeedometry in the aureole of the Ballachulish Igneous Complex, W. Scotland**

Lloyd, GE; Morgan, D; Jollands, M; Banks, D

**Significance of the anisotropy of magnetic susceptibility in fine-grained, siliciclastic natural and experimental rocks**

Haerinck, T; Debacker, TM; Sintubin, M

**Grain Growth in Halite**

Tant, J; Covey-Crump, SJ; Schofield, PF

**The fabric evolution with slip in natural cataclasites from seismogenic depths**

Mittempergher, S; Di Toro, G; Aretusini, S; Gratier, JP

**Poster session and lunch**

12:45-13:30

**Session 10: Structural Geology – General II**

Chair: Taija Torvela

13:30-14:45

**Geometry of the Achnashellach Culmination; forward modelling to analyse strain evolution**

Watkins, H; Butler, RWH; Bond, CE; Healy, D

**Retrograde deformation path recorded in fluid inclusions in syn- to late-orogenic vein quartz. Examples from the High-Ardenne slate belt (Redu-Daverdisse, Belgium)**

Jacques, D; Muchez, P; Sintubin, M

**Complex trishear propagation faulting and its potential application in natural structures**

Pei, Y; Knipe, RJ; Paton, D; Lickorish, H; Li, A

**Modeling two co-axial episodes of shortening with a deformed unconformity**

Deng, H; Koyi, HA

**Kinematics and internal deformation within 3-D granular slopes: insights from analogue models and natural slopes**

Liu, Z; Koyi, HA; Swantesson, J; Nilfouroushan, F

**Refreshments & poster clearance**

14:45-15:15

**Session 11: Regional Tectonics II**

Chair: Rick Law

15:15-16:45

**The tectonic history of the Rhodope Massif, Bulgaria: constraints from Sm/Nd garnet geochronology**

Collings, D; Savov, I; Eccles, K; Baxter, E; Harvey, J

**A crustal-scale extensional duplex within the Australia-Eurasia collision in Indonesia.**

Watkinson, IM; Hall, R; Hennig, J; Forster, M

**The structural evolution of Bukkalja (NE Hungary) based on field works and seismic section analysis**

Petrik, A; Fodor, L



### **Tectonic evolution of the Northern Damara belt, Namibi**

Lehmann, J; Naydenov, K; Saalman, K; Milani, L; Charlesworth, EG; Kinnaird, JA

### **Pliocene extension on Seram and Ambon, eastern Indonesia, linked to mantle exhumation and granulite-facies metamorphism**

Pownall, JM; Hall, R; Watkinson, IM

### **The mode of extension in the orogenic mid-crust revealed by seismic attribute analysis**

Torvela, T; Moreau, J; Butler, RWH; Korja, A; Heikkinen, P

### **Closing Remarks**

John Wheeler (chair of TSG)

16:45-17:00

## **DAY 4 – SUNDAY 6<sup>th</sup> JANUARY**

### **MOVE TRAINING COURSE, Midland Valley**

09:30-16:30

School of Earth & Environment, University of Leeds

*This course is now fully booked. Lunch is provided by Midland Valley.*

*Richard Phillips will escort attendees to the venue. Please meet in the foyer of The Queens Hotel at 09:00. Alternatively, meet at 09:30 at the main entrance to the School.*

### **Information for Speakers:**

All presentations (except keynote speakers) have a strict allocation of 15 minutes. You should aim to **speak for no more than 12 minutes**, allowing time for questions. This is important as the TSG General Meeting is a discussion forum. Session chairs will strictly enforce time limits. Keynote speakers should speak no more than 25 minutes, allowing 5 minutes for questions & discussion.

All presentations will be run from a central PC using **Powerpoint 2007**. Please ensure that your talk is compatible with this and is brought on a USB stick. Speakers will not be allowed to use their own laptops. Please upload your talks during the interval period prior to your session. All presentations are erased at the end of the conference.

### **Information for Poster Presentations:**

Posters are an important part of TSG General Meeting. They remain on show for the duration of the conference. Each display will be up to **A0 portrait** (boards are maximum 1m wide & 2m high). A successful presentation can be read from at least 1-2m away. Body text should be no smaller than 20pt font, with title text at 36pt or greater.

Posters should be displayed from 10am on Day 1 (Thursday 3<sup>rd</sup> January) and removed between 14:45-15:15 on Day 3 (Saturday 5<sup>th</sup> January). The organisers take no responsibility for posters displayed beyond 15:15 on Day 3. Poster boards will be removed after the final session.

**Oral Presentation Abstracts**  
(Listed by order of session time)

## Session 1: Fault Zone Processes I

### **Keynote Lecture: Geological constraints on fault dynamic weakening mechanisms from natural slip surfaces in carbonate faults**

R.E. Holdsworth (1)\* N. De Paola (1), F. Agosta (2), F. Balsamo (3), R. Bullock (1), E. Dempsey (1), I. Faoro (1), and F. Storti (3)

(1) Rock Mechanics Laboratory, Earth Sciences, Durham University of Durham (UK)

(2) Dipartimento di Scienze Geologiche, Università della Basilicata, Potenza (Italy)

(3) Dipartimento di Scienze della Terra, Università di Parma, Parma (Italy).

\*r.e.holdsworth@durham.ac.uk

Fault weakening ( $m_s < 0.2$ ) during earthquake propagation is now widely believed to occur due to a range of thermally activated, dynamic weakening mechanisms. Field and microstructural studies of seismically active fault zones can provide valuable constraints on the critical parameters and mechanisms of dynamic weakening.

We studied exposures of three well-exposed, NW-SE seismogenic extensional fault systems in the central-northern Apennines of Italy ( $M_w$  5-7; Umbria, L'Aquila, Fucino Basin systems). In all cases, fault displacements are accommodated in m- to dm-thickness fault cores comprising interlayered tabular domains of breccias, cataclasite and gouge. Slip is highly localized within narrow ( $<1$  mm) zones often bounded by polished, striated wavy to straight principal slip surfaces (PSS). Microstructurally, the PSS zones comprise juxtaposed layers of low porosity, coarse to ultra-fine grained cataclasite. Straight and sharp slip surfaces separate cataclasite and ultra-thin ultracataclasite layers ( $<50$  mm), characterized by the presence of abundant nanoscale particles. Slip zone asperity sizes range from a few mm (striated wavy surfaces) to sub-micron size (sharp, straight surfaces associated with ultracataclasites). Injected cataclasites indicative of fluidization processes are locally present.

Our preliminary observations suggest that the PSS zones are thin enough to promote thermally-activated dynamic weakening mechanisms. Such processes may be inhibited when the size of the asperity contacts is too small and the porosity too high and, in these cases, fault lubrication may alternatively be facilitated by the formation of nanoparticles.

## **Fault weakening across the frictional-viscous transition zone, Karakoram Fault Zone, NW Himalaya**

David Wallis<sup>\*</sup>, Richard J Phillips and Geoff E Lloyd

University of Leeds

\*eedw@leeds.ac.uk

'Weak' fault zones with coefficients of friction considerably less than Byerlee friction have been postulated on the basis of kinematic, heat flow and geometric considerations. More recently, experimental rock deformation studies have provided a variety of potential 'fault weakening mechanisms'. Fault zones exhibiting fault rocks formed in the frictional-viscous transition zone (FVTZ) that are now exposed at the surface provide a testing ground for the applicability of these weakening mechanisms to natural fault zones. The Karakoram Fault Zone (KFZ) is one such fault, displaying FVTZ fault rocks that show evidence of weakening mechanisms, including reaction softening, geometric weakening, pre-existing weak mineral phases and high pore fluid pressures. Fine grained phyllonites may have deformed by frictional-viscous creep with a low coefficient of friction. These observations indicate that the KFZ has had potential to act as a weak fault with a reduced coefficient of friction ( $\mu < 0.35$ ) and may provide an analogue for some presently active weak strike-slip faults at depth. The potential weakening mechanisms may provide one explanation for the present general lack of seismicity on the KFZ and the absence of large earthquakes along it in the historical record. In addition, evidence for brittle deformation is found on fault strands of the KFZ previously assumed to record only ductile shear, providing an insight into strain accommodation along the fault in the upper crust.

## Reduction of friction on faults by weak-phase smearing

A. Hackston, E. Rutter, E. Yeatman, K. Brodie, J. Mecklenburgh

School of Earth, Atmospheric and Environmental Sciences, Manchester

The apparent weakness of certain faults, particularly those unfavourably oriented with respect to the regional stress field, has been variously attributed to the development of high pore fluid pressures, the role of mechanically weak phases, deformation by pressure solution creep or some combination thereof. Here we consider the action of mechanically weak phases that can be mechanically smeared over the surface of thin, continuous fault planes.

We prepared synthetic fault gouges from quartz ‘flour’ mixed with kaolinite in the weight ratio 2:1 and various proportions of dispersed graphite. 0.7 mm thick layers were sheared under constant normal stresses up to 170 MPa. Friction coefficient decreased non-linearly between end member values of  $m_1 = 0.6$  and  $m_2 = 0.1$ , with very rapid decrease with only small proportions of added graphite, according to :

$$m_{\text{measured}} = (1 - a_2)^p / m_1 + (a_2)^p / m_2$$

in which  $a_2$  is the volume proportion of added graphite and exponent  $p = 0.7$ .

The effective area of weak phase on the shear surface was enlarged by mechanical smearing such that the smear-corrected area fits a linear mixing law between the end members. Exactly the same behaviour is known for metal matrix composites in which weak-phase smearing reduces friction between bearing surfaces. In rocks, we find that friction on smooth slip surfaces in organic-rich shales is reduced in the same way, and recently published data (Moore & Lockner 2011. *J. Geophys. Res.*, **116**, B01403, doi:10.1029/2010JB007881) on the behaviour of fault gouge containing talc follows the same rule. Any process, such as hydrothermal growth of weak phases on narrow slip planes can produce the same disproportionate effects. However, such weakening is not seen on rough fault planes, in which mechanical smearing does not produce contiguous layers.

## **Reactive transport modeling of fault-controlled fluid flow during growth of a normal fault network, Jebel Akhdar Dome, Oman.**

Stenhouse, P.<sup>1,2</sup>, Cox, S. F.<sup>2</sup>, Virgo, S.<sup>3</sup> Arndt, M.<sup>3</sup>, and Urai, J. L.<sup>3</sup>

<sup>1</sup> SRK Consulting UK Ltd; 17 Churchill Way, Cardiff, CF10 2HH, United Kingdom.

<sup>2</sup> Research School of Earth Sciences; Australian National University, Canberra, ACT 0200, Australia.

<sup>3</sup> Structural Geology, Tectonics and Geomechanics; RWTH Aachen, Aachen, Germany.

Fracture-controlled flow systems play an important role in fluid redistribution within the upper crust. However, the spatial and temporal distribution of flow in these systems is complex and not well quantified. This talk will combine mapping with stable isotope analysis of vein, fault and host rock material to explore the 4D evolution of fluid flow in the Dar Al Baydha (DAB) Fault; a large, vein-rich fault in northern Oman. The DAB Fault is a normal fault, but underwent minor dextral and sinistral slip reactivations. Fluid flow in this fault system was controlled by episodic fluid-driven failure. Hydrothermal calcite samples from the fault and associated veins are locally depleted in  $^{18}\text{O}$  by up to 12‰ relative to host rock, indicating that this fault system breached an external fluid reservoir. The distribution of  $^{18}\text{O}$ -depleted calcite varies both in space and time. During normal slip, low  $\delta^{18}\text{O}$  hydrothermal calcite was preferentially localised at fault segment boundaries and fault terminations. During subsequent sinistral reactivation, the distribution of low  $\delta^{18}\text{O}$  hydrothermal calcite is more variable, with no dominant structural control. Surrounding the DAB Fault is a network of subordinate faults with lengths typically <2000m. Hydrothermal calcite  $\delta^{18}\text{O}$  compositions in this fault network have a similar distribution to the DAB Fault. This indicates that this network was connected to the external fluid reservoir and hosted significant fluid flux. Reactive transport modeling of fluid flow in the DAB Fault infers local, time-integrated fluid fluxes (TIFFs) of up to  $10^6\text{mol}/\text{cm}^2$ , similar to TIFF estimates for some moderate-sized gold deposits.

## **Understanding the evolution of ultrasonic velocities in carbonate hosted normal fault zones**

Haines, TJ\*; Michie, EAH; Neilson, JE; Healy, D

Department of Geology and Petroleum Geology, University of Aberdeen

\*t.haines@abdn.ac.uk

A wide range of primary carbonate lithologies exist and can be modified by an equally wide range of diagenetic processes resulting in complex and heterogeneous carbonate fabrics. Further complexity can be introduced by regional stresses e.g. faulting, folding and related fracturing. Deformation and diagenesis can therefore create new fabrics or modify existing ones. The complex and heterogeneous nature of carbonate fabrics and the resulting pore networks ultimately controls the petrophysical signature of these rocks. Outcrop exposures in Malta are used to characterise the evolution of petrophysical properties, chiefly ultrasonic velocities in carbonate hosted normal fault zones.

This study focuses on the Oligocene Lower Coralline Limestone (LCL) Formation and the overlying Miocene Globigerina Limestone (GL) Formation. Textures in these two formations range from lime mudstones to grainstones. Normal fault zones, which dissect the stratigraphy, range in displacement from < 1 m to c. 60 m. Core plugs, made from field samples, have been used to quantify petrophysical properties (porosity,  $V_p$  and  $V_s$ ) in the fault zones. Image analysis, on three orthogonal thin sections, is used to define 3D pore network characteristics.

Core plug porosity ( $\phi$ ), sampled within and surrounding the described normal fault zones, ranges from < 5% to > 35%. Core plug ultrasonic P-wave and S-wave velocities range between 2 and 6 km/s and > 3 and 1 km/s respectively. In the FW of a given fault, p-wave velocity is observed to change from 3 km/s outside the fault zone to c. 6 km/s on the fault surface. The relationship between velocity and porosity is well known (e.g. Wyllie et al 1956), however, deviations away from these relationships can be explained by pore network characteristics (e.g. Weger et al. 2004). Preliminary image analysis results suggest pore size, shape and orientation impart a control on ultrasonic velocity.

## **Modelling a strike-slip fault system affecting porous carbonates in Favignana Island (Sicily, southern Italy)**

A. Cilona<sup>1,2</sup>; E. Tondi<sup>2</sup>; F. Agosta<sup>3</sup>; G. Johnson<sup>1</sup>; R. Shackleton<sup>1</sup>

<sup>1</sup>Midland Valley Exploration Ltd., Glasgow, United Kingdom.

<sup>2</sup>Geology Division, School of Science and Technology, University of Camerino, Italy.

<sup>3</sup>Department of Geological Sciences, University of Basilicata, Potenza, Italy

Understanding the deformation processes in carbonates is fundamental for geo-fluid exploitation. Indeed, in these rocks fluid containment and migration are influenced by fault zones and fractures.

This contribution integrates structural analysis and numerical modelling approaches aimed at testing a new workflow for creating a 3D Discrete Fracture Network (DFN) model of a reservoir from outcrop data. In Favignana Island (Italy), several quarries provide 3D exposures of Lower-Pleistocene grainstones crosscut by a strike-slip fault system. This fault system is comprised of three types of structures: compactive shear bands (CSB); zones of bands (ZB); and, faults.

The DFN model was built using the Fracture Modelling module within the Move software package from Midland Valley<sup>®</sup>. Analysis of an aerial photo was performed to identify the major faults. The intensity of CSBs and ZBs, was calculated from the lineament analysis tool of Move. We used the variation in intensity to build a DFN that reflects an intensity of deformation similar to the natural structural framework.

Both CSBs and ZBs reduce permeability whilst slip surfaces enhance fault-parallel fluid flow. The DFN was then used to model the effect of deformation on the permeability of the host rock by imposing a reduced permeability in CSBs and ZBs relative to the host rock and the slip surfaces.

This semi-automated process of lineament analysis, followed by the use of power law distributions to model sub-seismic scale features is proposed as a workflow for reservoir-scale assessment of the structural control on permeability in porous carbonate reservoirs.



## Session 2: Fault Zone Processes II

### **Influence of fault rock foliation on fault zone permeability: The case of deeply buried arkosic sandstones (Grès d'Annot, SE France)**

Thibault Cavailhes<sup>1</sup>, Pierre Labaume<sup>1</sup>, Jean-Pierre Sizun<sup>2</sup>, Alain Chauvet<sup>1</sup>, Roger Soliva<sup>1</sup>, Martine Buatier<sup>2</sup>, Delphine Charpentier<sup>2</sup>, Anna Travé<sup>3</sup> and Claude Gout<sup>4</sup>

(1) Géosciences Montpellier, UMR 5243, Université Montpellier 2-CNRS, Place Eugène Bataillon, 34095 Montpellier cedex 5, France.

(2) Chrono-Environnement, UMR 6249, Université de Franche-Comté-CNRS, 16 route de Gray, 25030, Besançon cedex, France.

(3) Departament de Geoquímica, Petrologia i Prospecció Geològica, Universitat de Barcelona, c/Martí i Franquès s/n, 08028 Barcelona, Spain.

(4) TOTAL, CSTJF, Avenue Larribau, 64018 Pau, France.

Fault zones are major discontinuities in sedimentary basins. Understanding their role on fluid migrations is an essential issue to (i) characterize the mechanisms and kinematics of deformation and (ii) to determine the parameters that control the distribution of energetic or mineral resources. This work applies to faulting under a temperature range of 200-250°C, corresponding to that of deeply buried reservoirs as well as potentially sismogenic fault zones.

The studied faults are normal faults affecting the “Grès d'Annot” formation, a Priabonian-Rupelian siliclastic turbidite succession of the alpine foreland basin. The “Grès d'Annot” were tectonically buried under the Embrunais-Ubaye Nappes soon after their deposition and exhumed during the middle-late Miocene. The studied area is located in the eastern part of the basin, where vitrinite reflectance indicates maximal temperatures of 220-240°C, i.e a burial depth of 7-8 km assuming a mean geothermal gradient of 30°C/km. The faults affect alternating arkosic sandstone beds and pelite layers with offsets from centimeters to decameters. The shear deformation affecting sandstone in the fault zone involves the combination of (i) pressure solution of quartz, (ii) intense fracturing sealed by quartz and calcite cements and (iii) the neoformation of (1) white micas derived from the alteration of feldspars and (2) chlorite. These mechanisms are responsible for a foliated fabric of the rocks in the fault core zone. Microthermometry of fluid inclusions and thermometric modelisation on newly formed chlorites suggest a fault temperature activity (220°C-240°C) consistent with the estimated maximal burial depth.

Combining a structural and microstructural study with permeability measurements on plugs oriented following the main axes of deformation (X, Y and Z), we show that the Y axis (parallel to the veins and cleavage) is the preferential direction of potential fluid flow in the foliated arkosic sandstones characterizing the fault zone ( $10^{-2}$  mD for Y against  $10^{-3}$  mD for X, Z and the protolith, measured at a confining pressure of 20 bars). We discuss also that the Y axis of deformation, which is parallel to the fault azimuth in the case of normal or reverse faults, is vertical in the case of strike slip faults. Hence, the preferential axis of fluid flow in the foliated fault rocks is, at all points of the fault zone, sub-perpendicular to the striation representative of the local movement, and this, at all scales.

## **Geometric analysis and scaling relations of lozenges and lenses in deformation bands and normal faults**

Abdullah Awdal\*, Dave Healy & Ian Alsop

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Deformation bands can act as barriers or baffles to fluid flow and it is therefore crucial to understand their geometric patterns. We present a quantitative analysis of lozenges in deformation bands. A lozenge is the area or volume of relatively undeformed rock situated between two strands of a composite deformation band. Cataclastic deformation bands and their patterns have been mapped and quantified in outcrops of aeolian sandstones of the Entrada formation in SE Utah (USA) and the Hopeman formation in Moray (Scotland). We propose a developmental model of lozenges based on the kinematics of deformation bands.

The geometry of lozenges can be related to the growth and linkage of deformation bands. We quantify the 3D geometry of lozenges from collected samples and *in situ* field measurements. The measured ratios of the lozenge and lens dimensions are compared to linear and power law best fit regressions. In addition, we provide a quantitative comparison of deformation band geometry in 2D and 3D from several different localities. We also investigate the statistical trends among different lozenge and lens datasets (Goblin Valley, Hopeman, Bartlett Wash) and explore their correlation to other attributes of the fracture pattern and petrophysical properties.

## **Effects of petrophysical anisotropy on fault stability in porous sandstones**

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This contribution describes anisotropic and heterogeneous microstructures within faulted high porosity sandstones, and explores the influence of these variations on the hydraulic and mechanical properties of fault zones. By integrating quantitative analyses of field, laboratory and digital image data we can begin to understand and predict the behaviour of fluids during and after faulting and infer the impact of petrophysical patterns on rock mechanics.

Porous sandstones sampled around a normal fault zone show anisotropy of petrophysical properties in three orientations (x; perpendicular to the fault plane, y; down dip to the fault and z; parallel to the fault plane) with respect to the fault plane related to microfracture type and distribution and variations in pore geometry. These variations are independent of sedimentary fabric permeability. Permeability data from over seventy oriented core plugs show overall preferential fluid flow ( $K_{\max}$ ) down dip to the fault plane while porosity values measured using a Helium porosimeter are comparatively isotropic. 2D image analyses from forty corresponding thin sections show variable porosities between orthogonally oriented sections with samples close to the fault slip surface showing higher porosity in an equivalent orientation to  $K_{\max}$ . Interestingly, with distance away from the fault slip surface, image analysis porosities are higher perpendicular to the fault plane compared to down fault dip, in contrast to the measured  $K_{\max}$  orientation. From these results we explore how changes to pore fluid pressure in the anisotropic pore space might impact the geomechanical risk for fault stability.

## **Discrete element modelling of the formation of layer-parallel veins in mechanically anisotropic multilayer sequences**

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Mechanical anisotropy caused by layering in rocks and the occurrence of pre-existing layer-parallel veins can have an influence on formation of subsequent layer-parallel veins. To systematically study what controls formation and distribution of layer-parallel veins, we use Discrete Element Modeling (DEM) with ESyS-Particle [1] to systematically vary internal strength parameters and stress states in multilayer sequences.

Numerical 2D rock samples consisting of spherical elements are prepared using an insertion based algorithm rendering isotropic randomised particle packings. Brittle failure is represented by the breaking of brittle-elastic bonds between these spheres, rendering a numerical material that shows a Mohr-Coulomb type failure envelope with a non-linear tensile region.

Four parameter sets of mechanical micro-properties of inter-particle bonds are defined in the models, essentially yielding a (1) competent and (2) incompetent matrix, a (3) vein material and (4) a vein-matrix interface. Each of these has been separately calibrated via an automated calibration procedure.

Calibrated multilayer models are repeatedly brought to extensional failure under changing effective stress states with constant strain rates. After each fracturing event, an insertion algorithm refills the open fracture with new particles of the initial particle size distribution. By re-fracturing the refilled material, the influence of pre-existing veins is studied by systematically varying the ratios of mechanical strength of vein, matrix and interface material. This allows to study the formation of fractures in relation to different ratios of competence as well as vein spacing and density. Different types of vein generation can be modelled e.g. ranging from crack-seal to anastomosing veins.

[1] ESyS-Particle, open source. <http://launchpad.net/esys-particle>

# **The influence of open fracture anisotropy on CO<sub>2</sub> movement in geological storage complexes**

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Carbon mitigation through the geological storage of carbon dioxide is dependent on the ability of geological formations to store CO<sub>2</sub>. Secure long-term containment needs to be demonstrated due to political and social drivers, meaning that containment must be verifiable over periods of 100-10<sup>5</sup> years. Oil and gas reservoir production data, and field evidence show that fracture networks have the potential to act as focused pathways for fluid movement. Fracture networks can allow large volumes of fluid to migrate to the surface within the time scales of interest. In this paper we demonstrate the importance of predicting the effects of fracture networks in storage, using a case study from the In Salah CO<sub>2</sub> storage site.

Our workflow combines well data of imaged fractures, with a discrete fracture network (DFN) model of tectonically induced fractures. The modelled and observed fractures have been compared and combined with present day stress data to predict the open fracture network. These predictions have been compared with InSAR imagery of surface uplift, used as an indicator of fluid pressure and movement in the sub-surface, around the CO<sub>2</sub> injection wells. The analysis shows that the permeability tensor with the greatest anisotropy, that for the DFN sub-set of open fractures, matches well with the anisotropy in surface uplift. Our results show that a workflow of fracture network prediction combined with present day stress analysis can be used to successfully predict CO<sub>2</sub> movement in the sub-surface at an active injection site.

## **Session 3: Basin Analysis I**

### **Geometry and kinematics of accommodation zones related to salt wall collapse.**

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In the U.K. Central North Sea, dissolution related collapse of host sediments at the crests of salt anticlines has resulted in the development of structural hydrocarbon traps along salt wall flanks, and stratigraphical traps deposited in palaeo-valleys along salt wall crests, that are difficult to characterise using seismic data alone. The capacity and integrity of these traps are strongly controlled by sub-seismic scale fault systems associated with collapse of the salt wall crest. An in-depth understanding of the three-dimensional structural styles that facilitate this collapse, and the accommodation zones that kinematically link different structural styles, are key to the successful evaluation and exploitation of both these, and similar traps worldwide.

Field data collected in the Paradox Basin, Utah, U.S.A., where equivalent structures are preserved and exposed at the surface, form the basis for the development of summary models representing the range of structural styles related to salt anticline collapse, and the three-dimensional geometry of the accommodation zones that are present both where different structural styles interact, and where salt walls terminate. Models show numerous sub-seismic scale faults with orientations that are controlled principally by the geometry of the underlying salt wall. Numerous small faults and fractures showing strike- and oblique-slip movement are present within accommodation zones and provide some insight into their development and kinematics. Early observations from Gypsum Valley, Colorado, suggest that these structural styles may be independent of scale. Developed models provide the basis of a framework for improving the interpretation of seismic data in salt-controlled hydrocarbon provinces.

# **Growth History of Fault-Propagation Folds and Interaction with Seabed Channels in the Toe-Thrust Region of the Deepwater Niger Delta**

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The deepwater fold and thrust belt of the southern Niger Delta has developed prominent thrusts and folds oriented perpendicular to the regional slope because of the thin-skinned gravitational collapse of the Niger Delta above the overpressured shale detachment of the Akata Formation. The growth of the thrusts/folds started approximately 7 Ma and many of the thrusts are still actively growing and influencing the pathways of modern seabed channels. We used 3D seismic reflection data to constrain and analyze the along-strike shortening of major thrusts/folds with seabed relief. Based on measurements of shortening, we have quantified the average strain rates of the different folds. We measured variations in fold crestal relief along-strike and used the growth sequences deposited as deformation is ongoing to measure incremental fold crest uplift through time.

Our study shows that the shortening varies along-strike for all folds, and range from less than 1 km to 4 km (equivalent to 9 – 38 % shortening). Variations in shortening along strike illustrate similar patterns to those observed on normal fault systems and we identify linkage between adjacent fold-propagation folds in regions of shortening minima. Calculated fold strain rates, averaged over a period of 7 Myrs, range from  $-1.5 \times 10^{-15} \text{ s}^{-1}$  to  $-6.5 \times 10^{-16} \text{ s}^{-1}$ . Similar to the shortening results, fold crest relief varies between structures and along-strike in any one structure.

Pleistocene to recent seabed slope channels are deflected and diverted by the active fault-propagation folds. We observe a variety of behaviours in how the channels interact with the active folds. As is expected, some channels exploit fold tips or relay positions to cross the structures; others however cross folds at the position of maximum shortening. Another factor that appears to affect channel behaviour is the width of the structure. The widest fold, with a crest up to 5 km wide (in comparison to the more typical fold crestal width of 2 km) causes diversion of a channel system for by 10 km along the strike of the fold. In contrast, the narrow structures tend just to deflect channels. Together, these results provide new constraints on the structure, geometry and time-integrated growth history of fault-propagation folds in gravity-driven systems, and demonstrate that such folds play a significant role in controlling sediment pathways in deepwater settings.

## Quantifying the timing and magnitude of fault reactivation in the northern North Sea

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Pre-existing normal fault populations influence the geometry and evolution of rifts that form in response to multiple extension events. The northern North Sea has experienced a number of extensional episodes, in the Devonian, Permo-Triassic and Mid-Late Jurassic. The importance of fault reactivation versus initiation is controversial, and few studies have quantified and compared fault activity in each rift phase. Using a combination of seismic and well data we quantify fault activity during the Permo-Triassic (PT) and Mid-Late Jurassic rift phase and determine the timing of fault initiation and reactivation on the eastern margin of the North Viking Graben.

We show that PT faulting was restricted south of 61°N on the Horda Platform, resulting in a total extension of 11.5 km ( $\beta=1.26$ ). North of 61°N, on the Måløy Slope, < 1 km ( $\beta<1.02$ ) of PT extension occurred. In contrast, during the Mid-Late Jurassic rift phase, extension was not focused on the Horda Platform, but was more widespread and resulted in more constant extension across the region reactivating PT faults where they existed, and initiating new faults in crystalline basement where no PT fabrics existed. Fault initiation occurred in the Middle Jurassic (ca. 165 Ma), whereas the PT fault reactivation occurred later and diachronously during the Early Cretaceous (ca. 150 and 130 Ma). We suggest that the primary control on rift development during the Mid-Late Jurassic was the strain gradient associated with lithospheric thinning in the North Viking Graben, leading to the development of new optimally positioned faults, in preference to reactivation of the pre-existing, PT fabric.



## **Recent Findings in the Geodynamic Evolution of the Equatorial Atlantic and their implications on Petroleum Systems**

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Recent discoveries in French Guiana (Zaedyus), and continued exploration success in the more established West African margin has maintained high exploration momentum in the Equatorial Atlantic. Current activities are focused on testing the Ghanaian 'Jubilee Play' in neighbouring basins and in the conjugate South American Margin.

Although the Late Cretaceous Fan System is widely recognised in the Equatorial Atlantic Margins, not all exploration has been successful. Several key factors have to be in place in order for the petroleum system to be productive, and these factors are governed by the timing and style of opening along the Equatorial Atlantic Margin.

Oil Company Geologists now realise that it is imperative to understand the early rift history (pre-Albian) of the Equatorial Atlantic. Knowing the extent and distribution of highly attenuated continental crust is of highest importance as it has implications for source rock distribution and thermal maturity of both syn-rift and post-rift source rocks. It is also important to understand the nature and timing of activity along the major Pan-African Shear zones and how they facilitated the early opening of the Equatorial Atlantic and subsequently influenced the drainage. The change from the pre-Albian configuration to that at present day also needs to be considered, as resultant transpression produced fold belts which influenced the deposition of post-rift source rocks and diverted the Late Cretaceous channels.

Getech are carrying out a Structure and Tectonics Study of the Equatorial Atlantic Margins including 1:1 million precision scale mapping of structures from potential field, SRTM and Landsat data, seismic interpretation and restoration, 2D gravity and magnetic profiles, depth to basement maps, crustal definitions and plate modelling. This study aims to answer key questions about a) the asymmetry, distribution and timing of rifting, b) the extent of highly attenuated transitional crust and the position of the COT/COB, and c) the interplay of Equatorial Atlantic opening with Central and South Atlantic opening.

## **Session 4: Structural Geology – General I**

### **Deformation mechanisms accommodating igneous sill emplacement in the Irish sector of the Rockall Basin**

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Magma intrusion within the subsurface is heavily influenced by the pre-existing architecture of the upper crust and, depending on the emplacement mechanisms, may modify basin structure and fluid flow pathways. Seismic reflection data reveal that intrusive networks predominantly consist of interconnected, saucer-shaped sills that are often associated with dome-shaped ‘forced’ folds generated by intrusion-induced uplift. However, fold growth and the interplay between accompanying ductile and brittle deformation styles remains poorly understood. Here, we use 3D seismic reflection and borehole data from the Irish sector of the Rockall Basin, offshore western Ireland, to quantitatively study eighty-two igneous intrusions that either have saucer-shaped, climbing saucer-shaped, planar transgressive or strata-concordant morphologies. Overlying these intrusions are a series of broad, domal-folds (>20 km diameter) onto which smaller, ‘parasitic’, monoclinial and domal-folds (~5 km diameter) are superimposed. Preliminary results suggest that these are forced folds that formed to accommodate the emplacement of the underlying igneous intrusions. We show that emplacement depth below the palaeoseabed and vertical stacking of the sills strongly influences forced fold development. Furthermore, it is apparent that laterally adjacent folds interfere with each other to modify fold geometries and produce a broader dome-shaped fold. A key observation is that many forced folds show little evidence for the development of contemporaneous, outer arc extension-related, normal faulting, which is often observed on forced fold crests. We suggest that the lack of faulting indicates that several other mechanisms, such as layer-parallel slip and porosity reduction, may have acted to provide space for the intrusion volume.

## **Inverted crater in the Nafud Basin: impact structure localises igneous tectonics**

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3D reflection seismic data in the Nafud Basin of northern Saudi Arabia image a crater at a depth of 3,800 m below the land surface. Named “Jalamid”, it is a 19 km diameter fault-bound structure at Lower Ordovician and Cambrian level with a pronounced central peak. The pattern of minor, kilometre-scale structures within the crater is consistent with generic internal structure of known impact craters. The crater is overlain by a shallow, Middle Ordovician flexural basin. A well has drilled the crater and shows that the Middle Ordovician strata are well-organised with low dips but the underlying Lower Ordovician strata are fractured and folded. Jalamid is a previously-unpublished crater that is not in the list of accepted or possible impact structures on Earth.

But the 3D seismic also show that the middle Ordovician to lower Silurian section is deformed into a dome whose location and radial extent closely matches the underlying crater and flexural basin. The doming event occurred after 1,500 m of isopachous deposition representing a time interval of some 30 million years after the cratering process. An alternative model would have the crater be an entirely blind, late Silurian structure contemporaneous with the dome, with sediment redistribution driving structural evolution. However, we argue against the synchronous model, showing that the evidence favours a Lower Ordovician cratering process, possibly impact, followed by Upper Silurian igneous intrusion and doming. This model implies that igneous intrusions in sedimentary basins might occasionally be associated with deeply-buried impact craters.

# **The intrusion ‘space-problem’: a case study of accommodation and deformation structures associated with the emplacement of the Maiden Creek satellite intrusion, Henry Mountains Utah**

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Most studies of sills and laccolith intrusions concentrate on their geometry and internal architecture, while only a few pay particular attention to emplacement-related deformation structures in the host rock that record how magma is accommodated within the crust, i.e. the ‘space problem’. This research aims to develop a greater understanding of how igneous intrusive bodies are emplaced and accommodated within the shallow crust.

Maiden Creek, a satellite intrusion to the Mount Hillers intrusive complex (Henry Mountains, SW Utah), is a sill-like body with a complex elliptical shape with several finger-like lobes. Field mapping and terrestrial laser scanning (TLS) techniques have been used to build a 3D structural model for selected areas of the intrusion and host-rock. Detailed outcrop studies across two neighbouring lobes have identified a sub-horizontal shear zone which runs along the top contact of each intrusive lobe. This shear zone separates low-/moderately-deformed sandstones above from highly deformed sandstones below and between the two lobes, hence acting as a detachment zone. Strain within the highly deformed sandstones is dominated by compressional faults, fractures and fabrics which point to a ‘bull-dozing’ mechanism for lobe emplacement. Fabrics (stretched plagioclase phenocrysts) within the igneous rock, seen on the upper surface of the intrusive lobes directly beneath this shear zone, show that the shear zone was contemporaneous with magma emplacement. The shear zone therefore appears to have played a critical role in accommodating magma emplacement.

## **Linear volcanic segments in the Sunda Arc, Indonesia, identified using the Hough Transform**

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The Hough Transform is used as an objective means to analyse volcano distribution in Java and Nusa Tenggara in the central Sunda Arc, Indonesia. Most Quaternary volcanoes define four en echelon, linear segments, each of 500 to 700 km length. Javan volcanoes that do not lie on these segments either (i) formed at an early stage in the history of the arc and are petrologically and geochemically distinctive, or (ii) lie along other mapped structures. The en echelon distribution of volcanoes in Java and Nusa Tenggara is best explained by tensional stress in the arc lithosphere originating from two possible sources. Orthogonal, or slightly oblique, rollback of the subducting Indo-Australian Plate may induce extension, or transtension. Downward flexure of the lithosphere, as a result of dynamic topography or loading by the arc, would establish arc-normal tension towards the base of the lithosphere, where magma is supplied to volcanic systems. Deviations from the en echelon distribution west and east of the central Sunda Arc can be understood as responses to specific stress fields in arc lithosphere of Sumatra and eastern Nusa Tenggara, respectively.

## Apparent structural movement paths (*asmops*), a 3D treatment of 3D shear zones

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Shear zones could potentially have involved any combination of simple and pure shear that could have varied in time or space during the shear. Here I resurrect the approach introduced in 1962 by the late Derek Flinn and plot on lower hemisphere equal area projections the *apparent structural movement paths* (*asmops*) as poles to pre-shear planar markers distorted across natural shear zones.

*Asmops* should be parts of great circles if due to simple shear or distorted hyperbola if due to pure shear. The aim here is merely to look at the shape of *asmops* for natural shear zones while constraining the orientations and shape of the ellipsoid that describes their bulk homogeneous strain.

*Asmops* associated with homogeneous strains are relevant to inhomogeneous strains in shear zones because they record different stages in the rotation of the same marker within the same general movement pattern. *Asmops* therefore represent the memory of progressive shear histories and may be inhomogeneous within a homogeneous reference frame.

Multiple trajectories of greatest elongation of pre-shear grain shape fabrics were traced in chalk across outcrops of shear zones in high-grade Proterozoic gneisses in Sweden. The poles to the foliation were plotted every decimetre or so along the chalk lines and the *asmops* interpolated between them. *Asmops* map the path followed by local X-axis during strain. All my results so far indicate significant proportions of pure shear. Future workers claiming that their shear zones involved simple shear must demonstrate that their *asmops* are parts of great circles.

## **Session 5: Neotectonics & Active Fault Processes I**

### **Keynote Lecture: Earthquake Cycle Deformation and the Strength of Continental Lithosphere**

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The last 20 years has seen a dramatic improvement in the quantity and quality of geodetic measurements of the earthquake loading cycle. In this paper we compile and review these observations and test whether crustal thickness exerts any control. We found 78 earthquake source mechanisms for continental earthquakes derived from satellite geodesy, 187 estimates of interseismic “locking depth”, and 23 earthquakes (or sequences) for which postseismic deformation has been observed. Globally we estimate seismogenic thickness to be  $14 \pm 5$  and  $14 \pm 7$  km from coseismic and interseismic observations respectively. We find that there is no global relationship between Moho depth and the seismogenic layer thickness determined geodetically. We also found no relationship between seismogenic thickness and proxies for the temperature structure of the crust. This suggests that the effect of temperature, so clear in oceanic lithosphere, is masked in the continents by considerable variation in lithology, strain-rate, and/or grain size. Elastic thicknesses from Bouguer gravity are systematically larger than the geodetic seismogenic thicknesses but there is no correlation between them. By contrast, elastic thickness from free-air methods are typically smaller than the geodetic estimates of seismogenic layer thickness. Postseismic observations show considerable regional variations, but most long-term studies of large earthquakes infer viscoelastic relaxation in the lower crust and/or upper mantle with relaxation times of a few months to a few hundred years. These are hard to reconcile with the higher estimates of elastic thickness. Our analysis of the geodetic data therefore supports the “crème brûlée” model, in which the strength of the continental lithosphere is predominantly in the upper seismogenic layer. However, the distribution of geodetic observations is biased towards weaker areas, and faults can also modify the local rheology. Postseismic results could therefore be sampling weak regions within an otherwise strong crust or mantle.

## **Interseismic strain accumulation across strike-slip faults in the Middle East**

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Large strike-slip faults play an important role in accommodating continental deformation and pose a significant seismic hazard in the Middle East, but to date there are few geodetic slip-rate estimates for many of these faults. We use Envisat InSAR measurements to study interseismic strain accumulation on strike-slip faults in Turkey and Iran, including the Ashkabad Fault in NE Iran.

We have measured interseismic deformation across the Ashkabad fault using 13 Envisat interferograms covering a total timespan of ~30 years. Atmospheric contributions to phase delay are significant and variable due to the close proximity of the Caspian Sea. In order to retrieve the pattern of strain accumulation, we show it is necessary to correct interferograms for differences in water vapour and atmospheric pressure. This has enabled us to robustly estimate the slip rate and locking depth for the Ashkabad fault using a simple elastic dislocation model. Our data are consistent with a slip rate of 5-12 mm/yr below a locking depth of 5.5-17 km for the Ashkabad fault. This slip rate is 2-3 times higher than previous geodetic estimates, with implications for both seismic hazard and regional tectonics, in particular supporting fast relative motion between the South Caspian Block and Eurasia.

We also present recent results from Eastern Turkey, where we have produced InSAR-derived velocity maps for five overlapping radar swaths, covering an area ~400 km × 400 km. We have combined these InSAR measurements with existing GPS data to construct a high-resolution strain field for Eastern Turkey.



## Session 6: Neotectonics & Active Fault Processes II

### Deformation processes along continental transform faults: the southern Dead Sea Fault System, Israel

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The sinistral Dead Sea Fault System is a NNE-SSW trending transform fault system that extends over 1000 km from the Zagros mountains in the north to the Red Sea in the south, separating the Arabian plate and Sinai sub-plate of Africa. Approximately 105 km offset has been accumulated, in two distinct periods, since fault initiation in the mid-Miocene: 60 km 20 – 18 Ma and 45 km within the last 5 Ma. There are many bends and offsets along the length of the fault, producing numerous pull-apart graben and associated pressure ridges.

The focus of the present study lies in the southern part of the system, west of the town of Elat in Israel. The local geology is well-exposed and can be broadly separated into three main groups: i) Precambrian basement and Cambrian sedimentary rocks; ii) Cretaceous sedimentary rocks; and iii) Neogene – Recent sedimentary rocks. The active Dead Sea Fault strand is not well expressed in this area, but there are a number of exposed scarps immediately to the west of the transform valley, juxtaposing Cretaceous rocks against Precambrian and Cambrian units, at the same topographic level.

The present talk focusses on how local structures are related to regional strike-slip tectonics and on spectacular exposures of gouge, breccia and cataclasites along large offset faults. These are ideal for studying upper crustal deformation processes and the ways in which weakening mechanisms may lead to shear localisation during faulting. The nature and distribution of near-surface Quaternary – Recent fault activity will also be discussed.

## **Observations of fault linkage and growth during the 2005 Dabbahu rifting episode from high-resolution airborne LiDAR and InSAR data.**

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A distinct feature of normal fault zones are their linkage zones where smaller fault segments connect forming larger continuous fault structures. While their influence on normal fault growth has long been recognised direct observations of their development are few and far between.

We combined high-resolution airborne LiDAR data with InSAR measurements from the recent Dabbahu rifting episode, which commenced in 2005 within the Afar Depression, to study progressive fault growth and linkage.

InSAR measurements can provide accurate maps of surface deformation over large areas (10s of km) with a precision in the range of mm and a spatial resolution of meters to tens of meters. However, without precise local digital elevation models (DEM) relating this deformation to individual surface features is impossible. In combining the 2 data sets we have been able to identify and quantify slip on individual fault zones.

During each dyke intrusion we observe reactivation of faults along the entire length of the dyke with several 10s of fault segments involved in each case. We can further see that the deformation is not just located along the obvious surface faults but that a considerable amount is located on buried structures. Here we focus on the deformation across a variety of linkage zones.

## **Comparing Long and Short Term Deformation in the Krafla Fissure System, NE Iceland, using LiDAR, InSAR and GPS**

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The Krafla volcanic system is situated on the divergent plate boundary separating Eurasia from North America, one of five fissure swarms (rift segments) in the Northern Volcanic Zone (NVZ) of Iceland. The Krafla segment is a 5-10 km wide and 100 km long region consisting of a central volcano and fissure swarm. Dyke intrusions and fissure eruptions characterise the activity in Krafla. A rifting episode in 1975-1984 activated an 80 km long segment of the Krafla fissure swarm.

The eruptive history suggests that the Krafla fissure swarm may not have been active for the whole of the last 10 ka, and that other rift segments may accommodate extension during periods of quiescence. Bjornsson (1977) estimated that the Northern Volcanic Zone has a major rifting event every ~ 100 years, each affecting only one of the five swarms. To better understand the deformation in this region we have attempted to determine whether faulting has been proceeding at a steady rate during this time period by examining both the long term (10 ka) and short term (10s of years) rates of vertical motion.

To study the short-term vertical deformation during the post-rifting period in the Krafla system we have combined a series of interferometric synthetic aperture radar (InSAR) images, acquired by ERS and Envisat, with GPS data. The GPS data constrain the horizontal deformation – we remove the contribution of horizontal motion from the InSAR data to isolate the current vertical surface deformation rates.

For the long term deformation, we have acquired high resolution LiDAR surveys over the Krafla fissure swarm in August 2007 and September 2008. We have interpolated these data to create a 1,300 km<sup>2</sup> high resolution (~0.5 m) Digital Elevation Model (DEM) of the area. Using the DEM and ages of known lavas, we have estimated the average rate of vertical deformation during the post-glacial period for an area north of the main Krafla caldera, covered by a 10 ka old lava shield.

Vertical deformation measurements made during the 1970s rifting episode have been used to calculate a possible average for cumulative rifting episodes as suggested by Bjornsson and a comparison of the observed long term deformation has been made to understand how much of the long term deformation is accounted for by rifting episodes alone. We will present a comparison of the long-term rates with the present-day deformation to determine whether the present-day deformation can be used as a reliable indicator of long-term rates of activity.

## **Lithological controls on the frictional behavior of a seismically active, upper crustal carbonate fault**

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The Gubbio fault (GF) is an active (1984,  $M_w = 5.6$ ) normal fault in the northern Apennines of Italy. It has accumulated >2 km displacement since the Miocene. We have studied a footwall section, where rocks have been exhumed from 2.5-3 km. The mid-Cretaceous protolith comprises two limestone members: a pale-yellow, micritic limestone and a red, marly limestone.

The majority of displacement is concentrated within a fault core of ~15 m width, which can be split into four structural domains (D1-D4), delimited by four major faults (F1-F4). In D1-D3, derived from the micritic limestone, rocks are heavily brecciated and slip confined mainly to principal slip surfaces. Microstructural analysis reveals shear localization zones, <25  $\mu\text{m}$  thick, composed of ultrafine, foliated, phyllosilicate-rich gouge.

In D4, derived from the marly limestone, deformation style is markedly different. Shearing is distributed throughout via an S-C fabric, defined by synthetic shear planes and phyllosilicate-rich pressure-solution seams; brittle deformation is rare. Microstructures within solution seams include kinks/folds in the phyllosilicates and pressure shadows around calcite clasts.

Brittle and localised deformation features in D1-D3 are typical of natural/experimental faults which have experienced rupture propagation, and are also associated with velocity-weakening behaviour, favouring earthquake nucleation. In contrast, structures in D4 are comparable to those obtained during experiments where rocks have behaved in a velocity-strengthening (aseismic) manner, deforming predominantly by pressure-solution creep. Thus the behaviour of the GF during the seismic cycle is likely to be complex, with interplay between brittle/localised (nucleation/propagation) and ductile/distributed (interseismic/post-seismic) deformation, influenced by lithological variations.

## **Earthquake focal mechanisms in anisotropic rocks and minerals: a cautionary tale**

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Many rocks and most minerals are elastically anisotropic. This has important consequences for the pattern of energy radiated by earthquakes that nucleate in these materials. In this talk we'll examine the effect of elastic anisotropy on earthquake focal mechanisms in 3 very different settings: 1) a single grain of quartz deformed in a controlled laboratory experiment; 2) a seismically active fault zone comprising mylonites exhumed along a crustal scale shear zone; and 3) laminated mudstones subjected to hydrofracturing (fracking).

Seismic sources with shear kinematics in isotropic materials produce only double couple (DC) signatures in the moment tensor, and there is a simple one-to-one correspondence between the kinematics of the source and that depicted by the DC 'beachball'. In contrast, seismicity in anisotropic materials can produce volumetric (ISO) and compensated linear vector dipole (CLVD) components, in addition to the DC component. The relative split between these components depends on: the strength of elastic anisotropy at the source; the kinematics of the source event with respect to the anisotropy; and the precise method used to decompose the moment tensor. This can make it very difficult to decipher the kinematics at the source region from the focal mechanism for events in anisotropic rocks. Great care is needed when interpreting the focal mechanisms, e.g. for stress inversions or regional tectonic syntheses.

## **Investigating fault friction by re-examining earthquake nodal plane dips**

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One of the major unresolved problems in geophysics concerns the frictional properties of active faults. Laboratory measurements of the coefficient of friction obtain a value of 0.6 (Byerlee, 1978), whereas several recent geophysical estimates found values less than 0.1 (e.g. Lamb, 2006; Herman et al., 2010; Copley et al., 2011).

We have assembled a catalogue of waveform-modelled fault plane solutions for earthquakes that occurred on continental dip-slip faults that have experienced only small displacements during their current phase of activity. Nodal planes for both thrust- and normal-faulting events are seen to spread between  $\sim 30^\circ$  and  $\sim 60^\circ$ , and are concentrated towards the centre of the range. This observed distribution suggests the reactivation of structures with a low coefficient of friction (less than  $\sim 0.3$ , and possibly as low as  $\leq 0.1$ ). We suggest this low coefficient of friction corresponds to the presence of weak materials in pre-existing fault zones.

## **Characterisation of active faulting in the Mongolian Altay Mountains based on previously unknown ancient earthquake surface ruptures**

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Earthquakes in continental collision zones are typically distributed across a region that may be thousands of kilometres away from the main collisional margin. This far-field deformation is poorly understood in terms of how strain is distributed onto upper crustal faults, particularly because active faults can be difficult to identify in regions where historical seismicity is sparse.

The collision between India and Asia forms the most impressive example of active continental deformation on earth, with several zones of faulting and uplift extending across a region over 2500 km wide. The Altay Mountains, western Mongolia, are at the northern edge of the India-Asia collision. Active dextral strike-slip faults in the Altay have produced M8 earthquakes and, according to GPS measurements, the region accommodates approximately 7 mm/yr of shortening. Surface ruptures of pre-historic earthquakes are exceptionally preserved due to the cold and arid climate of the Altay, and the size and expression of ruptures reveal important characteristics of the Altay active faults, such as typical earthquake magnitudes and definitive locations of active faults.

We present observations of, previously unknown, surface ruptures and active faulting from the Altay. The moment magnitudes of the ancient earthquakes are estimated based on the length of the ruptures using classic earthquake scaling laws, allowing us to place bounds on the rates and styles of faulting on a thousand-year time scale on the basis of total moment release. The rate and style of deformation from surface ruptures will be discussed in the context of the modern-day and long-term deformation in the region.

## Session 7: Regional Tectonics I

### Orogenic plateau growth: expansion of the Turkish-Iranian plateau across the Zagros fold-and-thrust belt

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This paper shows how the Turkish-Iranian plateau grows laterally by incrementally incorporating adjacent parts of the Zagros fold-and-thrust belt, within the active Arabia-Eurasia collision zone. The limit of significant, seismogenic, thrusting in the Zagros ( $M_w > 5$ ) occurs close to the regional 1250 m elevation contour. The seismicity cut-off is not a significant bedrock geology boundary. Elevations increase northwards, towards regional plateau elevations of ~2 km, implying that another process produced the extra elevation. Between the seismogenic limit of thrusting and the Zagros suture this process is plausibly ductile thickening of the basement, suggesting depth-dependent strain during compression. Underthrusting of the Arabian plate margin beneath Eurasia feasibly explains the high elevations on the Eurasian side of the suture. We estimate ~ 68 km shortening across the Zagros Simply Folded Belt in the Fars region, and ~120 km total shortening of the Arabian plate.

The Dezful Embayment is a low strain zone in the western Zagros. Deformation is more intense to its northeast, in the Bakhtyari Culmination. The orogenic taper (across strike topographic gradient) across the Dezful Embayment is 0.0004, and across the Bakhtyari Culmination, 0.022. Lateral plateau growth is more pronounced further east (Fars), where a more uniform structure has a taper of ~0.010 up to elevations of ~1750 m. A >100 km wide region of the Zagros further northeast has a taper of 0.002, and is effectively part of the Turkish-Iranian plateau. Internal drainage enhances plateau development, but is not a pre-requisite. Aspects of the seismicity, structure and geomorphology of the Zagros do not support critical taper models for fold-and-thrust belts, in particular the apparent lack of a regional detachment at the base of the deforming zone.



## How to restore the Anatolian continent and its suture zones?

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A good understanding of how suture zones can be restored to their pre-collisional setting is a pre-requisite for much geological research. Here we take the example of Anatolia which is littered with potential suture zones. Tectonic reconstructions of this region assume the existence of one or more continental fragments during Mesozoic-Early Cenozoic time. These are believed to have rifted from North Africa (Gondwana) during the Triassic, drifted across the Mesozoic Tethys and collided with Eurasia during latest Cretaceous-Palaeocene time. Current reconstructions range from one involving a regional-scale Tauride-Anatolide continent with oceanic basins to the N and S, to numerous rifted continental fragments separated by small oceanic basins. Tectonics-based evidence for the inter-relations of the continental blocks and associated carbonate platforms is summarised here, to distinguish between sutured oceans and intra-continental convergence zones in particular. Several crustal units are restored as different parts of one large Tauride-Anatolide continent, whereas several smaller crustal units (e.g. Kırşehir massif; Bitlis/Pütürge and Alanya/Kyrenia units) are interpreted as continental fragments bordered by oceanic crust. We infer a relatively wide İzmir-Ankara-Erzincan ocean in the N and also a wide S Neotethyan ocean in the S. Several smaller oceanic basins (e.g. Inner Tauride ocean, Berit ocean and Alanya ocean) were separated by continental fragments. Our proposed implications for tectonic processes, including rifting, subduction (and HP/LT metamorphism), thick vs. thin-skinned thrusting and continental collision.

Reference: Robertson, A.H.F., Parlak, O. & Ünlügenç, Ü.C. (eds) *Geological Development of the Anatolian Continent and the Easternmost Mediterranean Region*. Geological Society, London, Special Publication (in press).

## **Where the Caledonides overlaps the Grenville: The Grenvillian Glenelg Inlier as an allochthonous pip within the Moine fold-nappe complex, Scottish Caledonides**

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The Grenvillian (1100 – 990 Ma) and Caledonian (470-420 Ma) orogens were pivotal in building the Laurentia and Baltica continents. The two orogens are oblique and partially overlap in NW Scotland, where the Precambrian Glenelg Inlier in the hanging wall of the Caledonian Moine Thrust shows polyorogenic overprinting. Using new and hitherto unpublished mapping, we present a structural synthesis for the Glenelg Inlier and surrounding Neoproterozoic Morar Group (Moine Supergroup) metasediments. The inlier comprises the Western Glenelg Inlier composed of orthogneiss with no record of Grenville-age metamorphism, and the Eastern Glenelg Inlier, comprising ortho- and paragneisses that experienced Grenvillian eclogite-facies metamorphism. The Inlier and surrounding Morar Group metasediments were deformed by three generations of major ductile folds (F1-F3). In medium-strain areas, F2 and F3 folds (probably Caledonian) are coaxial and face west. Restoring for F2 and F3 shows the entire region is a fold nappe complex covering >20 x 60 km, comprising three parts:

- a) a complex hinge zone of recumbent isoclinal F1 folds, cored by Eastern and Western Glenelg gneiss, locally with sheared-out limbs;
- b) an ‘upper limb’ that is relatively low strained, broadly right-way-up containing a coherent Morar Group stratigraphy up to 8 km thick;
- c) a ‘lower limb’ comprising gneissose, sheared and inverted Morar metasediments.

The facing, transport direction and age of the F1 folds (Knaydartian?) remain uncertain. The Eastern Glenelg Inlier is a rootless isoclinal fold, allochthonous in three dimensions, and field relations do not constrain the exhumation mechanism from Grenvillian HP metamorphic conditions.

## **Hyperextension, rifted margin geometry and its incorporation into mountain belts: Insights from the western Alps**

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The distribution of hyperextended continental lithosphere at rifted margins, especially the presence of substantial tracts of hydrated upper mantle, is likely to have a strong bearing on subsequent orogenesis. Quantifying the magnitude and distribution of crustal thinning prior to orogenesis is critical for crustal balancing and the related prediction of subduction of continental crust. By invoking pre-orogenic hyperextension in the it is now possible to balance crustal sections western Alps so that the seismically imaged crust is consistent with estimates of orogenic contraction, without requiring long-term subduction of continental crust. Transitional parts of the ancestral rifted margin, appear to focus weak inversion ahead of the developing orogen. But the style of rifting (depth-heterogeneous vs quasi-uniform kinematics) controls which continental crust can later be subducted. That the continental crust of the internal basement massifs experienced transient subduction (HP peaks of 2-4 GPa) implies initially strong coupling with underlying mantle lithosphere (followed by decoupling for exhumation). These parts of the ancestral continental margin are thus likely to have stretched quasi-uniformly. However, those parts of the margin that stretched heterogeneously (rider blocks that rested on hydrated mantle) are less prone to subduction and thus show no UHP metamorphism (e.g. parts of the Briançonnais). The crust recycles without substantial burial, effectively concertinaing the rift blocks. The relative timing of contractional deformation in the subduction channel can therefore oscillate – without varying the far-field convergence rate. Lateral variations in margin geometry leads to complexly variable deformation timing but can still retain a broadly cylindrical orogenic structure.

## **The Carboneras Fault Zone, SE Spain: part of a stretching transform fault system**

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The Carboneras Fault Zone (CFZ), is a major NE-SW trending tectonic lineament in SE Spain, separating the volcanic Cabo de Gata terrain to the SE (accumulated over 18 to 6 Ma BP) from the tract of uplifted Alpine metamorphic basement blocks and post-orogenic basins that comprise the Betic Cordilleras lying to the NW. The fault system cuts metamorphic basement and folded post-orogenic sediments and volcanic rocks, and acted as a conduit for upper Miocene calc-alkaline volcanic rocks rising to the surface. NW of the CFZ, a series of unconformities and deformation episodes affect successive sedimentary formations of upper Miocene age (Upper Serravallian through Messinian). Movements on the CFZ are constrained stratigraphically by these unconformities. Older volcanics formed pre-faulting and are tilted to the vertical against the CFZ whilst the youngest volcanics step across the CFZ. A suite of Ar-Ar age determinations on amphibole crystals from the volcanics show that the main CFZ movements began 10.5 to 11.5 Ma BP and ended about 6 Ma, although lesser movement rates continue today. The CFZ is interpreted as part of a transform fault system separating NE-SW stretched and NW-SE shortened crust deformed above a south-westward retreating subducted slab, from a less deformed terrain lying to the south-east. Unlike the standard model of a transform fault cutting rigid plates, this is a stretching transform, a velocity discontinuity in a heterogeneously deforming crust and upper mantle sequence. Total offset in this area on the CFZ may be up to 40 km but is at least 15 km.

## Session 8: Basin Analysis II

### Has the western Greenland continental margin experienced depth-dependent stretching?

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The fundamental control on extensional basin formation and continental rifting is considered to be the thinning of the continental lithosphere. The aims of our study are to measure the magnitude of: 1) upper crustal and 2) whole lithosphere extension to investigate whether depth-dependent stretching models can explain the west Greenland continental margin evolution.

We have estimated the stretching factor ( $\beta$ ) from upper-crustal faulting for the crust and flexural backstripping, decompaction and reverse post-rift subsidence modelling for the lithosphere. Three seismic reflection depth profiles across the western Greenland continental margin have been studied. The northernmost Baffin Bay profile requires a lithospheric  $\beta$  factor varying from  $\sim 2.1$  in the NE to  $\sim 5$  in the SW. The central Davis Strait profile shows a gradual increase in  $\beta$  from NE to SW of  $\sim 1.5$  to almost infinity. The southernmost Labrador Sea profile requires a  $\beta$  of  $\sim 1.6$  to restore the continental platform. After 5 km of platform there is an abrupt increase of  $\beta$  to  $\sim 8$ . In contrast to the symmetric Labrador Sea and Davis Strait margins, the Baffin Bay area that appears to be more asymmetric.

Based on our analyses we find that the stretching factor ( $\beta$ ) from the upper crust faulting (typically  $\sim 1.1$  to  $1.4$ ) is less than the stretching factor ( $\beta$ ) from the whole lithosphere (from  $\sim 1.5$  to  $>10$ ). We conclude that the whole lithosphere has extended more than the upper crust and a depth-dependent stretching model is valid for the break-up evolution of the west Greenland margin.

## **The influence of Caledonian structures on Late Jurassic faulting offshore western Norway: new insights from 3D seismic reflection data**

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The architecture of the Jurassic North Sea rift has commonly been assumed to have been significantly influenced by crustal heterogeneities associated with the Caledonian orogeny and subsequent Devonian extension. However, evidence to confirm Mid-Late Jurassic reactivation of older structures is generally lacking due to the fact that the basement in the North Sea is generally deeper than the imaging capability of 3D seismic reflection data.

The Måløy Slope represents a basement high on the eastern margin of the North Viking Graben. Within this gneissic basement, three laterally-continuous reflections have been identified. The deepest of the three reflections is truncated by a N-S-striking, Mid-Late Jurassic normal fault system. Up to 600 m of throw has accumulated at the level of this intrabasement reflection, which is considerably larger than the maximum of 380 m throw observed at shallower levels (i.e. top basement), suggesting that this fault system nucleated within crystalline basement and propagated upwards into Mesozoic sedimentary cover.

We suggest that these intrabasement reflections may correspond to mylonitic shear zones produced by strain localisation during either SE-directed Caledonian compression or subsequent Devonian extension. This interpretation challenges the view that Jurassic rifting in the North Sea exploited pre-existing basement trends, and instead implies that a new fault system was generated during extension, obliquely cross-cutting the Caledonian/Devonian fabric. To our knowledge, this is the first example of a study where structures within crystalline basement have been mapped using 3D seismic data and their influence, or lack thereof, on subsequent fault patterns has been determined.

## **A Workflow for the Application of Critical Stress Analysis with Elastic Dislocation Modelling for Developing a Framework to Consider Likely Effects of Stress Anisotropy on Permeability within a Reservoir.**

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Intra-reservoir heterogeneity is widely recognised to affect fluid flow in reservoirs. Recent work has demonstrated the potentially significant influences of stress on structural features particularly below seismic resolution. This poster describes a workflow applied to gain a first-pass appreciation of the potential stress effects on interpreted faults and predicted features below seismic resolution.

Critical stress analysis is used to determine the potential influence of the contemporary stress field on the permeability of faults and fractures. Independently, elastic dislocation modelling is used to predict fracture distribution and intensity around the interpreted fault network.

This work considers the use of these methods combined as a tool for identification of broad areas in which fluid flow may be particularly sensitive to stress conditions. A number of key uncertainties are highlighted but overall the workflow is believed to offer a useful input for the consideration of stress effects on permeability anisotropy and structures below seismic resolution.

## **Relationships between tectonic fractures and cliffs morphologies: examples along chalk coast in France (Normandy, Picardy, Boulonnais)**

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Fractures, in particular master joints and faults, have an active role in the geomorphological development of the chalk cliffs. Each chalk district has its proper mechanical behavior inducing typical tectonic features in relation with geodynamics and large-scale tectonic paleostress. Master joints are defined as planar structures cutting the total height of a chalk cliff. They are repeating at equal distance with plumose and twist hackle steps. In some particular areas, flint filling is associated to jointing. In clayey chalk, hybride joints can be also very developed. Normal conjugated faulting is also observed with metric displacement. The evolution along the faults planes indicate frequently synsedimentary tectonics event. The faults are used to define the tectonic context in relation with the main geological events of the basin environment. But, the number of faults is quite small comparing to the jointing. These tectonic features have a direct impact on the development of the coastline, in terms of trending but also concerning slope development and local cliff morphologies.

Normandy and Picardy chalk districts are located in the most protected sedimentary deposit zones of the Anglo-Paris Basin far from the active crustal zone in Europe. Nevertheless the chalks deposits have recorded tectonic events mainly in relation with inversion tectonics and crustal development of the English Channel. In the Boulonnais, chalks fracturing are mainly influenced by the tectonic evolution of crustal Nord-Artois-Shear Zone.

Faults, joints and fractures have a strong influence on the hydrogeological dynamics in chalk rocks. Along the coastlines, different stages of alteration and excavations along the fractures can be observed with the appearance of major karstic features. The large development of caves at base of the cliffs, like near Etretat, results from initial chalk fracturing and local expulsiing of chalk alterite.

Comparative observations can be done between each chalk district to deduce a correlative analysis between chalk and fractures in view of characterizing the fractures network in terms of reservoirs behavior.



## **Pre-Arenig accretion history on the outboard (Monian) margin of East Avalonia, Anglesey, NW Wales.**

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Late Neoproterozoic accretion at the outboard margin of East Avalonia is recorded on Anglesey in ca. 650 Ma metamorphism in the Coedana Complex, the ca. 615 Ma supra-subduction zone Coedana Granite, and ca. 560 Ma exhumation of the Penmynydd Zone blueschists. Much of Anglesey's present architecture is though a product of orogenesis that commenced in the Early Ordovician when coaxial to intensely non-coaxial SE-vergent deformation assembled the Late Neoproterozoic rocks with the Middle Cambrian (to earliest? Ordovician) Monian Supergroup. This cycle is consistent with Penobscottian accretion in the northern Appalachians.

New BGS structural analysis in the New Harbour Group of western Anglesey identifies a km-scale SE-facing recliné synclinal fold complimentary to the well-researched Rhoscolyn Anticline. The lower limb (southern) of this Porth Penrhyn-mawr Syncline is dominated by NW-facing S0/S1 fabric relationships but D2 strain intensifies in this common limb both downwards towards the Rhoscolyn structure and upwards to the synclinal closure. The upper (northern) limb of the syncline is composite and dominated by intense non-coaxial strain. A strong SE-vergent D3 overprint transposes earlier fabrics and is associated with interleaving of slices of gneissose basement. In essence, the uppermost levels of this regional fold pair is replaced by a top-to-SE (D3) shear zone.

The Monian rocks were at surface (and deeply weathered?) before sub-aerial eruption of the (early Arenig?) ca. 200 m thick Church Bay Tuff Formation. The tuffs are overlain unconformably by a Middle Ordovician to early Silurian marine foreland basin succession, now arranged in a SE-vergent (Salinic?) thrust stack. All of this orogenesis pre-dates Acadian deformation.

## Session 9: Microstructural Analysis

### **Keynote Lecture: Quartz fabric-based deformation thermometry: examples of its application, relationships to petrology-based PT paths, and potential problems**

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The quartz c-axis fabric opening-angle thermometer proposed by Kruhl (1998, *J. Met. Geol.*, 16, 142-146) offers a potential analytical technique for estimating deformation temperatures in rocks deformed by crystal plastic flow. However, opening-angle is also sensitive to other variables such as strain rate, degree of hydrolytic weakening, and 3D strain type. Unless the influence of these individual variables can be quantified, use of fabric opening-angle as a deformation thermometer remains problematic and controversial. Over the last decade close correlations between: a) deformation temperatures indicated by fabric opening-angles and, b) temperatures of metamorphism indicated by trace element and mineral phase equilibria analyses, have been reported from a range of different tectonic settings, thereby arguably giving support to the use of opening-angles as a deformation thermometer. However, it needs to be demonstrated that the similar temperatures estimated by the different methods are related to the same geologic event, and therefore occupy at least a similar position on the PTt path - something that is in practice difficult to achieve for an individual rock sample. In cases where temperatures indicated by opening angles and mineral assemblages are markedly different, these differences could, for example, be explained by penetrative deformation and mineral growth/diffusion occurring at different times. Alternatively, when apparent deformation temperatures based on quartz fabrics are significantly greater than temperatures indicated by synchronous metamorphic mineral assemblages, this might be due to extreme hydrolytic weakening of quartz.

We illustrate this talk on the pros and cons of using fabric opening-angles as a deformation thermometer with examples from: a) Aureoles of forcibly emplaced plutons in the White-Inyo Range of eastern California where crystal-plastic deformation and recrystallization was short-lived and synchronous with contact metamorphism. b) Footwall to the South Tibetan Detachment in the Mount Everest area where deformation is demonstrably related to the exhumation stage of a petrologically well-constrained PT path. c) Hanging wall to the Main Central Thrust in the Sutlej Valley of NW India where deformation temperatures inferred from fabric opening angles are closely similar to temperatures of metamorphism indicated by garnet-biotite and oxygen isotope-based thermometry. d) Moine, Ben Hope and Naver thrust sheets of NW Scotland where structurally upwards-increasing deformation temperatures are compared with temperatures indicated by garnet-biotite thermometry. e) Mylonitic quartzites in footwall to Moine thrust at the Stack of Glencoul where hydrolytic weakening may have played an important role in deformation/recrystallization and associated fabric development. f) Thrust sheets in the Appalachians of Vermont that display a complex PTt history due to thrust sheet loading.

## **Quartz geothermometry and geospeedometry in the aureole of the Ballachulish Igneous Complex, W. Scotland**

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'Titanium-in-Quartz' geothermometry suggests quartzites can yield reliable temperature estimates. Four Ti-in-quartz geothermometers are applied to contact metamorphosed quartzites, Ballachulish Igneous Complex, Scotland. Two agree broadly with thermal modelling and pre-existing geothermometry whilst the others give temperatures consistently too low. All suffer from difficulties in analysing low Ti levels with high spatial and analytical precision, exacerbated by Ti heterogeneity within quartz grains. SEM-CL textures support Ti disequilibrium despite the presence of rutile, indicating a dynamic interplay between grain boundary diffusion, fluid/melt percolation and grain growth. but suggesting a geothermometer based on apparent volume diffusion of Ti in quartz to derive grain growth histories in samples proximal to igneous contacts. Analysis of rutile-quartz diffusion interaction implies peak contact temperatures of  $645 \pm 12^\circ\text{C}$ , more precise than Ti-in-quartz but reliant on external estimates of cooling rate from thermal models. All results demand caution in applying Ti-in-quartz geothermometry as calibrations vary by  $\sim 300^\circ\text{C}$  without means of identifying incorrect thermometer application, absence of equilibrium or degree of rutile activity. Greater understanding of Ti chemistry and fluid interactions, analytical limitations and equilibrium are necessary before Ti-in-quartz can be used reliably. However, quartz-rutile juxtaposition prior to heating to  $>600^\circ\text{C}$  defines a Ti diffusion thermometer if cooling rates are constrained by other means.

# **Significance of the anisotropy of magnetic susceptibility in fine-grained, siliciclastic natural and experimental rocks**

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The anisotropy of magnetic susceptibility (AMS) is a commonly used petrofabric tool. One of the standard graphs, used to illustrate the AMS evolution, is the Jelinek graph, in which the shape parameter  $T$ , used to discriminate between prolate ( $-1 < T < 0$ ) and oblate ( $1 > T > 0$ ) ellipsoids, is plotted against the degree of anisotropy  $P_J$ , expressing the eccentricity of the ellipsoid. Datasets of deformed sedimentary rocks show a distinctive pattern on a Jelinek graph. Although often interpreted in terms of tectonic strain, this  $T$ - $P_J$  pattern remains poorly understood.

We analysed and compared the AMS of fine-grained, siliciclastic rocks from three very distinct cases: 1) experimentally produced turbidites, 2) diagenetic, regionally undeformed Miocene sediments of the Waitemata Basin (New Zealand) and 3) deformed, low-grade metapelites of Palaeozoic Armorica (France). All three datasets show a distinctive pattern of constant to only slightly increasing  $P_J$  with slightly increasing  $T$  for prolate to somewhat oblate ellipsoids, changing to a constant to slightly increasing  $T$  with increasing  $P_J$  for more anisotropic oblate ellipsoids. When all three cases are brought together, it is possible to make up a conceptual model for the  $P_J$ - $T$  evolution of fine-grained sediments subjected to consecutive deposition, compaction and compressional deformation. However, there are large areas of overlap between different parts of the trajectory.

Our results demonstrate that careful consideration of the processes responsible for fabric formation and detailed, quantitative analysis of the magnetic carriers are of paramount importance for a correct assessment of the true significance of the AMS in fine-grained, sedimentary rocks.

## Grain Growth in Halite

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The grain growth kinetics of halite have been experimentally investigated by hot-isostatic pressing reagent grade halite powder (99.5 %NaCl) at 200 MPa confining pressure and different temperatures (330-600 °C) for durations ranging from 5 s to 120 days. The initial particle size of the halite was the 38-125 µm sieve fraction. During the initial stages of hot-pressing the halite recrystallized to a foam texture. Some porosity remained after recrystallization, the size and distribution of which appears to impact significantly on grain growth.

The grain size data are well described by the normal grain growth equation:

$$d^{1/n} - d_0^{1/n} = k_0(t - t_0) \exp(-H/RT)$$

where  $d$  is the final grain size,  $d_0$  is grain size at  $t_0$ , the time when the initial phase of recrystallization is complete,  $t$  is the duration of the experiment,  $n$  is the growth exponent ( $n = 0.25$ ),  $k_0$  is a constant ( $k_0 = 6.9807 \times 10^{10} \mu\text{m}^{1/n}\text{s}^{-1}$ ),  $H$  is the activation enthalpy ( $H = 120 \text{ kJmol}^{-1}$ ),  $R$  is the gas constant and  $T$  is temperature. The growth exponent suggests that growth is controlled by surface diffusion around pore boundaries, while the calculated activation enthalpy agrees well with that for the surface diffusion of  $\text{Cl}^-$  around halite grains.

Abnormal grain growth is observed in some of the higher temperature experiments, and current work is focused on establishing the extent to which this reflects the changing relative significance of pore size reduction and grain boundary mobility as temperature is increased. This is being done through grain size distribution and topology analyses in conjunction with SEM pore imaging.

## **The fabric evolution with slip in natural cataclasites from seismogenic depths**

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Faults in the seismogenic crust are often decorated by a layer of granular material, whose mechanical properties are controlled by mineral composition and fabric. Both evolve during fault activity, due to mechanical (grain comminution and abrasion) and chemical (mineral breakdown, mass transfer, cementation) processes.

We evaluated the effects of increasing shear strain on the fabric of small displacement faults in an ancient seismogenic fault hosted in tonalite and active at 9-11 km depth, typical earthquake nucleation depth in the continental crust. The samples were stem from cohesive cataclasites with slip of 0 – 4.7 m, measured on displaced dykes, and finite strain from 0 to 296. Sample textures were analyzed by means of quantitative microstructural measurements, Scanning Electron Microscope (SEM) Back Scatter Electron imaging and Energy Dispersive X-Ray Spectroscopy (EDS) equipped SEM for chemical mapping.

The grain size distribution is roughly power-law. With increasing finite strain: (i) the average grain size decreases (ii) the slope (D) of the bulk clast size distribution in two dimensions increases from 1.2 to 2.0 (iii) layers of highly comminuted, high D (up to 2.8) cataclasite are found for bulk finite strains higher than 82. Domains of foliated cataclasite are instead dominant in samples with bulk finite strain lower than 80.

The development of a layer of fine grained, evolved material is thus associated with thinning of the cataclasite layer, and possibly strain weakening behavior. Coarse grained, foliated cataclasites, are proportionally thicker, suggestive of strain hardening behavior and stress driven fluid-rock interactions overprinting the cataclastic deformation.

## **Session 10: Structural Geology – General II**

### **Geometry of the Achnashellach Culmination; forward modelling to analyse strain evolution**

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Since the first in depth report of the Moine Thrust Belt by Peach et al (1907) the area has been studied extensively and is known to exhibit a range of thrusts geometries (eg from multiple detachment levels, thrust reactivation and roof thrust breaching (McClay & Coward, 1981); the Achnashellach Culmination forms part of the Southern Moine Thrust Belt and displays similar complexities.

The field area studied exposes repeated packages of folded and thrustured Torridonian Sandstone and overlying Cambrian quartzites. Because of the area's high relief, well exposed vertical sections provide excellent cross section views through the thrust structures. Previous work on this culmination (Butler et al, 2007) suggests shortening is achieved by a series of imbricate thrusts with a single lower detachment within the Torridonian Group.

Detailed mapping and outcrop photographs provide evidence for multiple thrusting events; flat on flat geometries on clustered thrusts branching from a floor thrust near the base of the Cambrian define the first stage. The second event is characterised by ramp on ramp geometries where Torridonian Sandstone is carried over Cambrian sediments and, in places, can be seen to cross-cut older structures.

Forward modelling on a series of parallel cross sections constructed across the Achnashellach Culmination highlight how structures evolved through time; how the presence of older, Cambrian-involved structures affect the development of later, Torridonian-involved thrusts and how strain has developed during the evolution of the culmination.

## **Retrograde deformation path recorded in fluid inclusions in syn- to late-orogenic vein quartz. Examples from the High-Ardenne slate belt (Redu-Daverdisse, Belgium)**

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Fluid inclusion microthermometry of orogenic vein quartz, which formed under low-grade metamorphic conditions in the High-Ardenne slate belt (Redu-Daverdisse, Belgium), reveals a retrograde deformation path of the compressional stage of the Variscan orogeny. Three vein types were selected: *tension gashes*, arising from outer-arc extension of fold hinges; *saddle reefs*, i.e. dilational sites originating from flexural-slip; and *lenticular veins*, kinematically associated with parasitic folding along a tectonic ramp. These veins represent sites of transient structural permeability and express the brittle accommodation during different stages of folding. Both the saddle reef and the lenticular vein evidence free polycrystal growth without collapse and weak intracrystalline deformation, suggesting high fluid pressures and a late-orogenic origin, respectively. The lenticular vein is clearly bimodal, with a strongly deformed periphery of small, anhedral grains, and a weakly deformed core of large, blocky crystals.

Compiling trapping conditions of the primary fluid inclusion assemblages, a retrograde path can be determined from peak metamorphic conditions ( $\sim 310^{\circ}\text{C}$  and  $\sim 190\text{MPa}$ ), recorded in the tension gashes and the periphery of the lenticular vein, to lower metamorphic conditions (down to  $\sim 200^{\circ}\text{C}$  and  $\sim 150\text{MPa}$ ), recorded in the late-orogenic saddle reef filling and the lenticular vein core.

The microthermometric data allow to constrain the relative timing of the different veining events and associated stages of folding during the gradual uplift of the slate belt from  $\sim 7.5$  km to  $\sim 6$  km depth. Assuming a comprehensible anticlockwise metamorphic path, pore fluid factors that confirm the presence of high fluid pressures throughout this compressional stage, can be derived.



# **Complex trishear propagation faulting and its potential application in natural structures**

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The line-length imbalance is observed in some natural structural structures, resulting in the inapplicability of the typical fault-related folding mechanism. The trishear algorithm was proposed as an advanced faulting mechanism that allows line-length imbalance within the fault zone. However, the simplest single and constant dipping trishear faulting models are still not comparable with the complex natural structures. The uncertainty on the trishear parameters' physical properties and internal relationship inhibit trishear mechanism's further application. In this study, three aspects contributing to the trishear complexity are discussed: (a) the faults with upward-changing dip angle, (b) the combination of multi-faults and (c) the lateral variation along the structure strike. A range of complex trishear models are simulated based on these three complexities. The experimental physical models are brought in to compare with the models, revealing the validity of trishear mechanism in complex structures.

Given the line-length imbalance of trishear models, here the forward trishear modelling is more applicable to analyse the deformation history rather than the conventional balancing restoration. An example of a well-constrained seismic section of Lenghu5 thrust belt in northwestern China is also reported in this study, to illustrate the trishear application in a complex natural structure with line-length imbalance. The application of complex trishear faulting mechanism increases the accuracy of fault zone interpretation that is limited by the seismic resolution.

## **Modeling two co-axial episodes of shortening with a deformed unconformity**

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Analogue sandbox models are used to simulate two co-axial episodes of shortening. Erosion and sedimentation after the first episode yield an angular unconformity which is subsequently deformed by the second episode of shortening. Model results show that, the bulk thickness of deformed sand package together with the thickness ratio ( $T_2:T_1$ , where  $T_1$  and  $T_2$  are thicknesses of sand package beneath and above the unconformity, respectively) govern the final structural style. During the second shortening phase, some of the pre-existing thrusts are reactivated, and new thrusts are initiated. In the models, new thrusts are different in number and spacing. The pre-existing structures influence the spacing of the second generation thrusts. A low thickness ratio ( $T_2:T_1 \approx 1:3$ ) tends to create a pop-up structure between kink folds and significantly increases displacement along individual reactivated thrusts. In contrast, a high thickness ratio ( $T_2:T_1 \approx 1:1$ ) reactivates more pre-existing faults. However, in this case displacement along individual thrusts is relatively small. Although the presence of a weak layer on the unconformity boundary does not detach the upper units from the lower structure, it seems to prevent reactivation of pre-existing thrusts. Displacement distribution along a reactivated thrust roughly shows an abrupt change across the unconformity, with the amount of displacement decreasing discontinuously up-section. This feature may help to distinguish a reactivated thrust in the field.

# **Kinematics and internal deformation within 3-D granular slopes: insights from analogue models and natural slopes**

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This study uses results of a series of analogue models, scanned data of natural landslides, and sections of natural failed slopes to investigate the kinematics and internal deformation during the failure of an unstable slope. The models simulate collapse of granular slopes by focusing on the spatial and temporal distribution of their internal structures. Model results show that the collapse of granular slopes resulted in different-generation extensional normal faults at the back of the slope, and contractional structures such as overturned folds, sheath folds and thrusts at the toe of the slope. The failure surfaces and the volume of the failure mass changed both spatially and temporally. Our model results show also that the nature of runout base has a significant influence on the kinematics and internal deformational structures. The runout distance increased with decreasing basal friction of a rigid runout base, and the topography at the slope toe was much gentler in the model with lower basal friction along the rigid runout base. The runout distance was shortest in the granular slope with deformable runout base. More extensional normal faults occurred in the model with low-friction runout base, whereas more shortening structures formed in the model with high-friction runout base. Similar to model results, our field observations indicate the presence of at least two generations of failure surfaces where the older ones are steeper.

## Session 11: Regional Tectonics II

### **The tectonic history of the Rhodope Massif, Bulgaria: constraints from Sm/Nd garnet geochronology**

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Newly discovered diamond inclusions in garnet delineate the Rhodope Massif (RM) as a globally important UHP locality. All available protolith and metamorphic ages from the RM are based on accessory minerals like zircon and monazite, and these tend to cluster in a confusing array of ages spanning from pre-Variscan to post-Alpine (Eocene) times. There are 4 confirmed UHP localities across the RM, and all UHP indicators are restricted to garnets from metapelites. This study is the first to date the host of the UHP indicators, eliminating the risks of interpretations based on inherited inclusions. Bulk garnets and 4 zones from within a single large garnet crystal (d=2cm) have been dated via Sm/Nd geochronology. Bulk garnet ages reveal three distinct populations ca. 90 Ma, 80 Ma and 70 Ma, which appear to correlate with age zones from the single garnet crystal, and well-known magmatic episodes across the area. Current tectonic models for the RM invoke either a protracted subduction cycle with a single, long lasting (>30Ma long) exhumation event, or a series of complex subduction -exhumation cycles and record of multiple suture zones. We will attempt to link our garnet Sm/Nd ages with the complex pre- and post-Jurassic tectonic evolution of the RM, and in particular we will clarify the much debated question of the nature of the exhumation events.

## **A crustal-scale extensional duplex within the Australia-Eurasia collision in Indonesia.**

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Low-angle mylonitic fabrics from the metamorphic basement of central Sulawesi, at the convergent triple junction between the Australian, Eurasian and Philippine Sea plates, reveal a complex history of extension from the late Miocene to the present-day.

Mylonitic fabrics are widespread in a suite of metamorphic complexes that include mica schists, migmatites, eclogites, marbles and garnet peridotites. Kinematic indicators record transport directions between top-to-the-NW and top-to-the-NE. Medium to high-grade mylonites are associated with ductile boudinage of amphibolite, eclogite and kyanite-bearing layers, 'snowball' garnet porphyroclasts, dynamic recrystallisation of feldspar and amphibole, and mylonitic deformation was locally synchronous with partial melting.

Mica growth during mylonitic deformation is recorded by  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  plateaux between  $5.05 \pm 0.01$  Ma and  $2.07 \pm 0.03$  Ma in the west and  $11.33 \pm 0.02$  Ma in the east. Undeformed aplitic dykes cross-cut the mylonites and have yielded a biotite  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  plateau of  $3.62 \pm 0.02$  Ma. In the east the mylonitic fabric is cut by a low-angle detachment surface expressed as anomalously corrugated topography.

The central Sulawesi metamorphic complexes consist of a series of low-angle ductile shear zones comprising a crustal-scale extensional duplex, cut by an upper brittle detachment which may still be active. The system is bounded by the active strike-slip Palu-Koro and Matano faults, which may flatten at depth into a basal detachment below central Sulawesi. Early extension may have been driven by east-directed rollback of the Banda Sea. Later extension (post-5 Ma) was driven by Celebes Sea subduction rollback in the north.

## **The structural evolution of Bukkalja (NE Hungary) based on field works and seismic section analysis**

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Bukkalja is located south of the Bükk Mountains in Northeast Hungary. It is a typical foothill area made up of mainly Paleogene limestone, siliciclastic rocks, several early to mid-Miocene tuff horizons as well as Late-Miocene and Quaternary sediments. The main task was to determine the different stress fields and fault patterns focusing on mainly Miocene period. More than 1000 structural data were collected in 76 quarries and outcrops covering the entire investigated area. 115 sets of stress axes were calculated and integrated into the main deformation phases based on relative chronology, syndiagenetic structures and seismic section analysis. We also suggested the existence of some new faults on the area based on geological maps, morphological features and structural data.

Field works were complemented with 2D seismic section analysis focusing on structural interpretation of the Vatta-Maklar Trough (subsurface equivalent to Bukkalja). 9 time horizons were digitized on seismic sections representing the main unconformities, lithological, magnetostratigraphical and parasequence boundaries of the territory. Faults identified on seismic sections were correlated to each other in order to perform the fault polygon maps of the territory. These polygons were also compared to faults derived from field works. The most important fault lines are ENE-WSW trending ones (master faults) accompanying with en-echelon faults resulting in a complex fault patterns of the trough. Based on analysis the Vatta-Maklár Trough was created as a pull-apart basin by the ENE-WSW trending oblique left lateral faults in early Late-Miocene (between 11.6-9.2 Ma) during the post-rift stage.

## **Tectonic evolution of the Northern Damara belt, Namibia**

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Detailed descriptions of structures associated with remote sensing analysis and microstructural observations were performed in the Northern Zone of the Damara orogenic belt (Namibia). Passive margin siliciclastic and carbonate sequences of the Neoproterozoic Damara belt were polymetamorphosed to the biotite zone of the greenschist facies and polydeformed during pene-coeval late Neoproterozoic to late Cambrian closure of two highly oblique oceanic domains: the NS trending Adamastor Ocean to the west and the NE-SW trending Damara Ocean in the study area. Subtle relict structures and fold pattern analyses reveal the existence of an early N-S shortening which was then almost obliterated by a pervasive and major E-W shortening, related to the closure of the Adamastor Oceanic domain and subsequent formation of the NS striking Kaoko belt to the West of the Northern Zone. Early km-scale E-W trending steep folds were refolded during this event, producing either Type I or Type II fold interference patterns visible in remote sensing images. During final NW-SE convergence in the Damara belt, a rigid Paleoproterozoic basement-high located north of the Northern Zone indented the weak metasedimentary rocks and produced a deformation front on its southern edge. The NW-SE convergence is responsible for NW-verging asymmetric metre-scale folding associated with top-to-the-NW shear zones and km-scale bending around a vertical axis of the Type I and Type II refolded folds. Variations in map shapes of these spectacular fold interference patterns will be discussed as well as the tectonic significance of these deformation events for the evolution of the Damara belt.

## **Pliocene extension on Seram and Ambon, eastern Indonesia, linked to mantle exhumation and granulite-facies metamorphism**

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The Banda region of eastern Indonesia accommodates the complex convergence of the Eurasian, Australian, and Pacific plates. The island of Seram, which lies in the northern part of the 180°-curved Banda Arc, has previously been interpreted as a fold-and-thrust belt, incorporating ophiolites, that has been formed during arc-continent collision. However, new mapping and observed field relations show evidence for rapid recent extension and cast doubt on this interpretation. Widespread lherzolites, which form a complex with 3–16 Ma granites and granulites, show no evidence that they belong to an ophiolite and instead have been exhumed along low-angle NNE-dipping extensional detachments (W Seram) and by left-lateral strike-slip pop-up structures (central Seram). The granites, which contain abundant cordierite and garnet phenocrysts and sill+sp restites, show evidence for generation by *in situ* anatexis of high-T grt+crd+sill+sp+crn+qtz granulites, with both the high-temperature metamorphism and subsequent anatexis driven by their juxtaposition against the hot mantle peridotites. THERMOCALC P-T modelling, used to produce a P-T pseudosection for 16 Ma granulite sampled from the Kobipoto Mountains, indicates temperatures of 850–1050°C at ~7 kbar and potentially records ultrahigh-temperature (UHT) peak metamorphic conditions (>900°C). Furthermore, rapid (>3 mm a<sup>-1</sup>) rates of exhumation are indicated by <sup>40</sup>Ar/<sup>39</sup>Ar geochronology recording complete recrystallisation of micas in schists and cordierite granites between 5.9–3.4 Ma. Geophysical evidence (Bouguer gravity ‘highs’ and seismic tomography) and plate reconstructions support major extension in the Seram region driven by Pliocene subduction rollback of the Banda Arc that has exhumed the upper mantle and deep crust.



## **The mode of extension in the orogenic mid-crust revealed by seismic attribute analysis**

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The processes and the structures within the middle and the lower crust are intimately related to the evolution of orogenies, but these deep crustal processes are still poorly understood. Seismic reflection data, chiefly displayed in amplitude, are commonly used to interpret deep crustal structures. The strongest amplitude events are probably related to lithological changes and do not necessarily correspond to structural boundaries or to deformation fabrics. Furthermore, the detailed structures and the strain distribution between the interpreted structural boundaries remain obscure. Here, we show how seismic attributes, combined with the seismic facies interpretation technique, can be used to enhance 2D seismic reflection data from the Palaeoproterozoic Svecofennian crust of southern Finland, to reveal unprecedentedly detailed information about the deformation fabrics within orogenic mid-crust. The images are plausibly interpreted to show that the extension/flow of the orogenic middle and lower crust was mainly accommodated by mega-scale S-C' structures. The structures form penetrative deformation fabrics which are correlated with outcrop observations. The successful enhancement of the seismic data confirms the ductile extension affecting hot orogenic crust, and gives new information about the strain distribution of the regional, syn- to late-orogenic deformation.

**Poster Presentation Abstracts**  
(Listed alphabetically by first author)

## **Structural Interpretation of the Yasamal Anticline, Eastern Greater Caucasus Mountains using Terrestrial Laser Scan data**

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The Greater Caucasus mountain range connects the Caspian Sea with the Black Sea and is a part of the Alpine–Himalayan orogenic belt that was created as a result of the Arabia Eurasia-plate collision.

The study objective is to understand the detailed structures and tectonics of eastern Greater Caucasus belt, using a geological and structural database constructed from geological maps, field data and terrestrial laser scan data. Surface geology and its relationship to subsurface structures has been constrained, with emphasis on the eastern side of the mountain belt, by constructing geological cross sections along the Greater Caucasus at different scales.

Detailed maps and cross sections of a well-exposed fold structure (Yasamal anticline) using structural data have been constructed. By including laser scans which cover an area of about a square kilometre in the region of the southward plunging fold hinge, we have interpreted the bed-scale geometry, faults, small folds and other key structural features, and constructed a 3D model using Midland Valley's Move software. This has allowed us to investigate strain accommodation mechanisms using 3D Move to iteratively unfold the Yasamal structure, reconstruct the pre-folding templates and predictively model the fold-related deformation at small-scale.

## **Statistical analysis of fracture trace angles to guide models of 3D fracture orientation**

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Fracture orientations are intrinsically three dimensional, yet useful data can be extracted from field measurements of fracture trace angles along one dimensional scan lines or boreholes, and on two dimensional rock surfaces. We present a statistical analysis of fracture trace angles to guide the estimation of 3D fracture orientations from 1D and 2D measurements. This is important for models or software that use idealised distributions (e.g. Fisher or Watson distributions) to populate 3D orientations from lower dimensional datasets.

Our statistical analyses of fracture trace angles are for single fracture sets collected from outcrops in three different settings: faulted siliciclastics, USA; fractured basement, Scotland; folded carbonates, Kurdistan. Data were measured along 1D scan lines and 2D trace maps. We also calculate 2D trace angles from 3D strike and dip orientations of fractures by a geometrical apparent dip method on arbitrarily inclined rock faces, and calculated the circular mean, mode and standard deviation for each population. Fisher and Watson distributions in 3D should produce a normal distribution of trace angles on a 2D surface. We test this hypothesis with Normal and Weibull probability plots in the MATLAB™ Statistical Toolbox to compare the distributions of trace angles to the Normal distribution. We also quantify the degree of fit (or misfit) to the Normal distribution.

## **Investigating the subtle fabrics of the Ben Loyal Syenite**

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The late Caledonian (c. 426Ma) syenite intrusions of Loch Loyal; the Ben Loyal, Ben Stumandach and the Cnoc nan Cuilean intrusions were intruded into Moine and Lewisian metasediments. The Ben Loyal intrusion itself can be split into two distinct bodies, a subsolvus foliated outer portion and a hypersolvus structureless inner core. The foliations in the outer portion are generally concordant to the margins except in the SE where they seem to parallel regional tectonic fabrics. The emplacement of these bodies was therefore probably controlled at least partially by pre-existing structures. However the transition between concordant fabrics and regional fabrics is ambiguous due to the lack of structural data in the unfoliated inner core. Anisotropy of magnetic susceptibility (AMS) measurements can reveal subtle fabrics that are not otherwise visible. To examine any potential fabrics in the unfoliated core and to quantify further the visible fabrics in the outer core samples were taken from both the inner and outer regions of the intrusion for AMS analysis. With this data we hope to reveal any subtle fabrics in the inner core and to test the relationship between in the inner and outer cores. The overarching aim is to test the hypothesis that this intrusion was dominantly controlled by existing structures.

# **The influence of pre-rift structures on early stage rifting: Insights from the Barmer Basin, Rajasthan, India.**

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Structural geometries are key components of any sedimentary basin and are critical to understanding the petroleum plays within it. Basin-wide structural evolution is controlled by the regional stress field; however, large variations in fault styles, geometries and interrelationships occur due to inhomogeneities inherent in the pre-rift geology. It is during the early stages of rifting that such pre-existing inhomogeneities have the greatest effect on basin architecture which, in turn, controls early depocentre location, provenance and sediment routing.

The Barmer Basin, Rajasthan, India, is a Paleogene, extensional basin dominated by a continental fill. The complex and variable nature of structures generated during rifting are well highlighted along the eastern basin margin, but the orientation and interrelationships of these structures do not conform well to established extensional models.

In this work, we present detailed structural mapping and kinematic analysis to provide well-constrained insights into the evolution of the basin margin local to the study area. Here, a complex fault network includes sets that trend both obliquely and parallel to the regional tension. We develop 3D kinematic structural models to explain observed relationships in terms of the geometric interaction between rift-related and pre-rift structures, particularly as rift-structures hard link during early basin evolution.

The models demonstrate the important control that pre-rift structures can have upon early basin evolution. They also highlight the effect that complex structural geometries developed during the initial stages of basin evolution can have on the evolution of the basin as a whole.

## **Styles and timing of emplacement of a saucer-shaped sill in the Exmouth sub-basin, offshore NW Australia**

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The delivery of magma from the mantle to the Earth's surface occurs via the formation of an intrusive interconnected network of conduits and reservoirs; the architecture of which influences eruption processes, sedimentary basin evolution and hydrocarbon systems. It is therefore fundamental to determine the relative age relationships between igneous products and the stratigraphic and structural features within a sedimentary basin.

This project utilises high quality 3D seismic data to examine the style and timing of a saucer shaped sill from the Exmouth sub-basin, part of an ancient volcanic rifted margin offshore NW Australia. Previous study has focused on basin wide compartmentalisation due to igneous intrusion. Here we look specifically at how igneous sills locally affect petroleum systems through the formation of forced fold trap structures generated by intrusion induced uplift. In particular we address how fault reactivation has influenced the accommodation space for the sill and/or the fold which is poorly understood. The volume of the forced fold is calculated giving a potential reservoir size whilst an understanding of faulting through the fold helps determine trap quality. An intrusion model is developed from the sill morphology. Furthermore, associated volcanism with the sill is studied along with potential hydrothermal fluid pathways.

To understand the detailed geometry of the intrusion the top and base of the sill was mapped in 3D. Adjacent sedimentary horizons and associated extrusions were also mapped. Age relationships were determined using stratal relationships. 3D fault geometries were mapped and fault timing determined through throw-depth plots.

## **Controls on the seismic properties of Moine Thrust Zone quartzites – quartz or mica?**

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It is well known that micas are one of the most seismically anisotropic minerals, whilst quartz may act to 'dilute' the overall seismic properties of a rock even when exhibiting a strong crystallographic preferred orientation (CPO). To assess the relationship between these two conflicting behaviours, a suite of natural samples of mylonitised Cambrian Quartzites from the Moine Thrust Zone, NW Scotland, has been investigated via a 'rock-recipe' approach. Results indicate that a maximum of 20-25% of mica is sufficient to control the seismic properties of the quartzites. Although the idealised average mica content (~17%) of Moine Thrust Zone quartzites is below the threshold required for it to control whole rock seismic properties, nevertheless in most samples mica forms the 'seismically dominant' mineral phase. The results show also that the  $V_p/V_s$  ratio, which is used frequently as a proxy for rock type, depends on CPO and can vary significantly with orientation (i.e. plunge-azimuth) of the incoming seismic waves. Such behaviour could impose significant constraints on geodynamic interpretations based on seismic profiling. Finally, the availability of precise location data for each sample has allowed the seismic properties to be plotted geographically within the Moine Thrust Zone using surface modelling and contouring software. Results, whilst indicating the need for denser sampling, reveal useful preliminary insights into the seismic property distributions of Moine Thrust Zone quartzites.



## **Precambrian discontinuities within the Torridonian Sandstone across the Beinn Eighe lateral ramp**

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Distinct compartmentalisation of the Moine Thrust Belt architecture is apparent across the Loch Maree Fault (LMF) at Kinlochewe in the Northwest Highlands of Scotland. Contrasting thrust architectures across the LMF are attributed to differential kinematic development believed to be a response to a step in basement, which generated a transport-parallel lateral ramp or sidewall during thrusting - the Loch Maree Transverse Zone (Kelly, 2012).

This work examines step-like thickening of the Torridonian rocks which occurs southwards of the LMF, across the Beinn Eighe massif within the trailing edges of the thrust sheets that make up the Achnashellach Culmination. These features may potentially be linked to a LMF-parallel or sub-parallel set of discontinuities, which control (lateral) thrust architecture as the Achnashellach Culmination thins step-wise northwards towards the LMF.

Recent detailed fieldwork focused on the Beinn Eighe massif has allowed the construction of several transport-direction-parallel/transport-lateral cross-sections which highlight distinct thickness changes of Torridonian strata contained within the Coire nan Clach and Creag Dhubh thrust sheets. These lateral structures are believed to be related to, or a subsidiary of the LMF, separating c.200m thick imbricate slices of Torridonian Sandstone in the north from c.1000m sections farther south.

Preliminary models attribute changes in thickness to pre-existing basement structures related to Precambrian extension, elements of which are believed to be connected to the transverse system found at Loch Maree. New cross-sections have been analysed along with stratigraphical separation diagrams to derive the pre-thrust template for the Beinn Eighe sector of the Moine Thrust Belt.

Kelly, M.J., Leslie, A.G., Clarke, S.M., and Williams, G.D. (2012) '*Cross-strike Discontinuities: The development of the Loch Maree Transverse Zone*' Oral Presentation, Tectonic Studies Group Annual Conference (TSG), Edinburgh, United Kingdom.

## **Occurrence and mechanisms of pseudotachylyte formation in the Gairloch Shear Zone**

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The Gairloch Shear Zone, a NW-SE band of localised Laxfordian to Grenvillian brittle-ductile shearing, contains examples of supposed pseudotachylyte veins associated with late-stage brittle 'crush' belts within the Loch Maree Group supracrustals and Lewisian gneiss of NW Scotland. Whilst these are previously described and dated in the literature, uncertainty remains as to whether all mapped occurrences are pseudotachylyte, and additionally what mechanisms might trigger and control the formation and distribution of pseudotachylyte during movement episodes. A series of potential pseudotachylyte veins were sampled in the Gairloch area from the 'crush belts' observed by previous workers to lie along lithological boundaries. Veins were identified by injection geometries, fracture associations, distinct vein margins and dark glassy matrix, with subsequent microscopic analysis allowing assessment of how well these accepted criteria can identify pseudotachylyte in the field. In contrast to previous reports, most pseudotachylyte was found in the amphibolite units rather than the semi-pelites or felsic gneisses, and not necessarily directly within zones displaying highest levels of brittle strain. It is possible that specific deformation processes localise the mechanisms of frictional melting and injection within a fault zone, overriding higher melting temperatures for mafic mineralogies. This study forms part of a PhD project employing field, optical and electron microscope techniques to investigate the deformation processes that facilitate frictional melting and pseudotachylyte injection during coseismic slip events.

## **Strain-Partitioning in an Oceanic Shear Zone: Carrick Luz, Cornwall**

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The Lizard Complex, Cornwall, preserves a section through a piece of oceanic crust, forming a northwards-younging sequence of peridotite, gabbro, and sheeted dykes. At Carrick Luz, 1-2 km below the Moho transition zone, a ~200 m wide dyke-like body of gabbro intrudes mantle peridotites. The gabbro intrusion shows a penetrative mylonite fabric, and discrete ultramylonitic shear planes, through to cataclasites and fault gouges. The mylonite fabrics are cut by relatively undeformed mafic (gabbro and basalt) dykes. Shear zone kinematics are dextral for all of the fault rock types, which, after correction for the regional tilt of the ophiolite section, are consistent with normal faulting. The gabbro mylonites are amphibolite facies and indicate deformation at about 750°C. Cataclasites and gouge, and chilled (basalt) dykes cutting the gabbro mylonites, indicate progressively lower temperatures during deformation (greenschist facies and below). Internally the gabbroic shear zone is dominated by L-S-tectonites (L>S), which grades to local zones of strongly-developed L-tectonites (<40 m wide). Zones of S>L-tectonites (<1 m wide) are spatially associated with lenses of peridotite (<2 m wide), which exhibit brittle deformations. Ongoing work aims to characterize deformation mechanisms as a function of distance from the peridotite lenses, and to constrain the effect of lenses on the strain gradient, and type, across the shear zone. Thin sections cut in the principal planes of the finite strain ellipsoid will be used to determine strain vectors within each domain, to quantify displacement associated with the Carrick Luz shear zone.

## **Structural setting of the Plio-Quaternary Campidano graben (Sardinia)**

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The Campidano graben is a regional structure in Southern Sardinia wide about 20 km and strikes NW-SE for 100 km from the Oristano to Cagliari gulf. It is superimposed on Oligo-Miocene basins with the same trending direction and filled by Middle-Upper Pliocene to Quaternary continental sediments. Although this is the most important structure related to Plio-Pleistocene tectonic activity in Sardinia, until now, no detailed studies on the geometry and kinematic evolution of the trough have been made.

We present new data on the structural setting of the Campidano graben, obtained from the interpretation of the available on-shore and off-shore seismic lines (provided by the Progemisa S.p.A. and Regione Sardegna), calibrated with 4 wells and integrated with other geophysical and geologic data.

The southern Campidano is characterized by normal faults bounded both the edges of the trough. Instead, the northern part is probably a semi-graben, with a normal fault along the western edge striking N-S and E dipping. These two parts are separated by the structural high of Sardara-Guspini. Furthermore, volcanic activity (6 ma-lower Pleistocene), is mainly concentrated in the northern Campidano. According the main authors, the Campidano graben is generally considered as originated by extensional tectonics which affected the western Mediterranean during Plio-Quaternary and the formation of the eastern margin of the Island. Nevertheless, the kinematic and dynamic evolution of this structure is partially unknown and with this study we are going to unravel the role of Sardinia during the opening of the South Tyrrhenian sea in Upper-Miocene to Quaternary.

# **The relative importance of brittle versus crystalplastic deformation mechanisms in quartz in the semi-brittle-regime**

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Conjugate sets of intracrystalline shear bands in quartz have been studied comprehensively. Concerning the relative importance of brittle versus crystalplastic deformation mechanisms in the formation of shear bands, different models are proposed: (1) shear bands initiate as microfractures parallel to the rhombohedral planes; subsequent shear activation causes a passive rotation of brittle fragments, which are subsequently affected by a dynamic recrystallisation; (2) shear bands develop by kinking produced by basal slip, followed by polygonisation by subgrain rotation recrystallisation; (3) shear bands develop by precursory Dauphiné twinning, followed by dynamic recrystallisation and grain boundary sliding in well-oriented twin domains.

In the vein quartz of well-studied veins in greenschist metamorphic metapelites of the High-Ardenne slate belt (Belgium, France, Germany), conjugate sets of intracrystalline shear bands are common. These veins are considered to have been formed and deformed in the semi-brittle regime. Therefore, this vein quartz seems very appropriate to study the relative importance of brittle and crystalplastic deformation mechanisms in the development of shear bands.

This research is performed by an integrated approach using Hot-CL, SEM-CL and EBSD. Attention is paid to the relationship with other deformation features, such as deformation lamellae and Dauphiné twins. Preliminary results, demonstrating the added value of the integrated approach, are discussed and compared to the different models for the formation of shear bands.

## **A reappraisal of the deformation history, kinematics and absolute age of faulting in the West Orkney – Orcadian Basin system, Caithness, Scotland**

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The faults and Devonian sedimentary rocks of the Orcadian Basin are used as a surface analogue for the fractured reservoir sequence of the offshore Clair field. New field and microstructural analysis reveals two distinct groups of faults and associated structures cutting the Devonian rocks and their immediate basement in the northern coastal region of Caithness:

‘Group 1’ faults trend N-S, NW-SE and WNW-ESE and display predominantly sinistral strike-slip to dip-slip extensional movements. Gouges/breccias associated with these faults display little or no mineralization or veining. The faults form the dominant structures in the eastern part of the northern coastal section in Caithness.

‘Group 2’ faults trend mainly NNE-SSW, NE-SW and E-W and display predominantly dextral to extensional displacements. Characteristically the faults are associated with widespread syn-deformational carbonate mineralisation (+/- pyrite and bitumen) both along faults and in mineral veins. These faults dominate the western parts of the coastal section and become less widespread east of Dunnet Head. Folding (mm to m scale), previously attributed to regional inversion, is almost always associated with Group 2-age strike-slip reactivation of Group 1 fault zones. Preliminary Re-Os pyrite and bitumen geochronology suggest that early Group 2 structures formed during the early Mesozoic in association with hydrocarbon generation.

We propose (at least) two distinct phases of rift-related faulting:

- A Devonian episode of ENE-WSW extension (Group 1) related to regional sinistral transtension along the Great Glen Fault and;
- An early Mesozoic episode of NW-SE extension (Group 2) that partially reactivated earlier structures.

# **Mobile Evaporite Controls On The Structural Style And Evolution Of Rift Basins: Danish Central Graben, North Sea**

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The Southern Tail-End Graben, Danish Central Graben, is characterised by a lateral variation in the thickness and mobility of pre-rift Zechstein Supergroup evaporites, allowing investigation of how supra-basement evaporite variability influences rift structural style and tectono-stratigraphy. The study area is divided into two structural domains based on interpretations of the depositional thickness and mobility of the Zechstein Supergroup. Within each domain we examine the overall basin morphology and the structural styles in the pre-Zechstein and supra-Zechstein (cover) units.

The northern domain is interpreted to be free from evaporite-influence, and has developed in a manner typical of brittle-only, basement-involved rifts. Syn-rift basins display classical half-graben geometries bounded by thick-skinned faults. In contrast, the southern domain is interpreted to be evaporite-influenced, and cover structure reflects a southward increase in the thickness and mobility of the Zechstein Supergroup evaporites. Both fault-related and evaporite-related folding are prominent in the southern domain, together with variable degrees of decoupling of sub-Zechstein and cover fault and fold systems. The addition of mobile evaporites to the rift results in: i) complex and spatially-variable modes of tectono-stratigraphic evolution; ii) syn-rift stratal geometries which are condensed above evaporite swells and over-thickened in areas of withdrawal; iii) compartmentalised syn-rift depocentres; and iv) masking of rift-related megasequence boundaries. Through demonstrating these deviations from the characteristics of rifts free from evaporite-influence, we highlight the controls evaporites may exert upon rift structural style and the stacking patterns within syn-rift successions.

## **Interpretation of 3D fracture linkage and fluid flow characteristics based on dyke intrusion patterns**

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Faults and dykes are three-dimensional structures and they are closely related, as pre-existing fractures are often used as conduits for fluid flow. Dykes can be emplaced along pre-existing fractures or create their own fractures, as well as sometimes being deflected along horizontal layers to form sills. Dykes provide excellent evidence of the way fluid flows through fractures in rocks and can act as agents in preservation of the fluid flow capabilities of fault systems. At coastal platform outcrops in Goseung, South Korea, we analyzed outcropping dykes, measuring variations in dyke thickness and fracture patterns around the dykes. Some dykes show clear evidence of intrusion along pre-existing fractures, especially along linkage damage zones of faults. We were able to infer the stage of linkage between two fault segments at the time of intrusion. Fluid flow occurs more readily along planes closely aligned so that they strike perpendicular to the direction of least compressive stress, and along fractures with a high degree of connectivity. At fault tip and linkage damage zone there is a concentration of extensional fractures which often form areas of increased permeability. Fault growth occurs through the linkage of segments at interconnected tip damage zones of unconnected fault planes. As faults become linked the fracture density increases, until they become fully linked and act as one through-going fault plane. These fault evolution stages are well recorded in the fracture patterns around the dykes, and they give an insight into fluid flow characteristics depending on the maturity of fault systems.



## **Tectonic control on pressure regimes: lateral drainage and Tertiary loading in the Jeanne d'Arc Basin, Eastern Canada**

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Highly variable mud weight profiles and reservoir pressure tests in the Jeanne d'Arc Basin (JDB) suggest there is a large variation in the distribution and magnitude of overpressure in the area. In this poster we describe the tectonic history of the basin and its result on both shale pressure and sandstone pressure.

Shale pressure in the basin is controlled by the existence of multiple unconformities which can allow pressures in shales to re-equilibrate to normal pressure. Tertiary loading since the unconformity therefore controls shale pressure sub-unconformity.

Sandstones of the same age and depth penetrated by different wells often show a variation in magnitude of overpressure ranging from hydrostatic pressure to highly overpressured ( $>45\text{mPa}$ ). The range in pressures is caused by the ability of fluids in the sandstone to escape by lateral drainage. Lateral drainage in the JDB is controlled by connectivity of sandstones to a fluid drainage pathway, out of the basin horizontally and vertically to reservoirs outcropping at the sea bed or onshore.

Three episodes of rifting and differential subsidence have led to a series of horst-graben systems and unconformities. The structural complexity of the JDB results in complex sand and shale juxtapositions across faults. Sandstones can therefore become isolated from the main pressure system responsible for lateral drainage and therefore become balanced with shale pressure.

Consequently, pore pressure prediction in the Jeanne d'Arc Basin becomes very challenging and a good understanding of 3D structural evolution of the basin, in addition to 1D well-based workflows, is essential.

## **Effects of mineralogical variations in sandstones on deformation mechanisms during normal faulting**

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Feldspars tend to fracture more easily than quartz grains due to a well defined cleavage. Therefore an increase in the amount of feldspar in a sandstone may affect the mechanisms and degree of deformation in the brittle regime. In this study, mineralogical variations within two distinct sandstone units cut by normal faults are investigated to explore for any mineralogical control on the dominant deformation mechanisms and the potential consequences for petrophysical heterogeneities around each fault zone. The host rocks are an aeolian sandstone with <10% K-feldspar content and a fluvial sandstone with >10% feldspars.

SEM-CL and BSEM images show that in rocks with higher feldspar content, feldspars are cataclased and smeared out whereas in rock samples with lower feldspar content the feldspars fracture but remain intact while quartz grains fracture and break into small microclasts. Comparison of undeformed host rock with damaged rocks shows volume change in the fault zone via cataclasis and dissolution of grains associated with fluid flow. Dissolved grains are dominantly feldspars due to an inferred chemical instability. Therefore the shapes, modal abundances and distributions of deformed feldspars may exert important influences on the current porosity and connectivity of pores around a fault zone.

## **Kinematics of transpressional structures in the Bahia basin, Colombian Caribbean.**

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High quality 3D seismic reflection data, regional 2D seismic reflection lines, together with well data from the Bahia Basin (Offshore Colombia) are used to investigate the kinematics of transpressive structures in the NW corner of South America, where a complex history of subduction, accretion and transpression is ongoing since Cretaceous times. The Bahia basin is located just offshore from two major strike-slip fault systems that affect northern Colombia, the E-W trending right-lateral Oca Fault and the NNW-SSE trending left-lateral Santa Marta-Bucaramanga Fault. The basin lies behind the South Caribbean Deformation Zone, the toe of the modern accretionary wedge, where the Caribbean Plate is being subducted obliquely beneath South America.

We have mapped a wide range of structures in the Bahia basin. There is a young, deep, narrow basin trending NE-SW which is bounded to the NE by a major fault. This fault shows an initial phase of normal displacement with later inversion along some segments. Its footwall appears to be formed by three separate blocks. An important upper Miocene unconformity is recognised within these blocks and high-density, low-displacement, normal faults are found below the unconformity. Intriguingly the trend of the normal faults varies from block to block within the footwall, which may indicate vertical-axis block rotation linked to the opening of the young depocentre.

In contrast, SW-NE trending folds affect the sediments above the upper Miocene unconformity which most likely have formed due to shortening related to subduction along the South Caribbean Deformation Zone. An understanding of the kinematic evolution of these structures will improve our knowledge of the complex array of structural styles that develop at a transpressive plate boundary.

## **Fracture networks and associated local stress fields in asymmetric folds at Saundersfoot, the South Wales Coalfields**

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Fracture networks have great effects on permeability and fluid transport in many hydrocarbon reservoirs. There have been many studies in the past decades on the development of fracture patterns in relation to regional-scale fold formation with a view of understanding better the permeability of oil and gas reservoirs. However, no clear and generally accepted relationships between them have been established as yet, but the topic continues to be of major interest in the petroleum industry. Here we report the results of a study of fracture networks in alternating sand-shale layers at outcrop-scale in relation with map-scale asymmetric folds in Saundersfoot in the South Wales Coalfields. A total number of 1,879 fractures have been studied. The fracture populations can be divided into two main relative-age groups based on the field observation. The older group constitutes fractures generated during extensional sub-parallel to the map-scale fold axis; the younger group constitutes fractures formed during extension sub-perpendicular to the fold axis. The fractures in both groups are either extension or hybrid (extension and shear) fractures. Many extension fractures in the sandstone layers become arrested at the contacts with the shale layers; those fractures that penetrate the shale layers are mostly hybrid and tend to have smaller apertures than the pure extension fractures in the sandstone layers. The results have clear implications for the vertical permeability of reservoirs composed of similar layers and indicate that the horizontal permeability is, for such reservoirs, much greater than the vertical permeability.

## **Evolution of Cretaceous conjugate faults in the Exmouth Sub-basin, offshore NW Australia**

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The evolution of rift-related normal fault arrays strongly influences the architecture of sedimentary basins. Here, we use high quality 3D seismic reflection data to analyse the development of a conjugate normal fault network in the Exmouth sub-basin, offshore NW Australia. Previous studies on conjugate faults focus mainly on the lateral development and spatial distribution; however the vertical migration, block movement and subsequent influence on fluid flow are still not fully understood.

As a multiple rift phase setting, the Exmouth sub-basin provides an ideal study area to understand the age relationships of the faults and fault evolution. By investigating the temporal and spatial development of these faults from two distinct rifting phases we can begin to understand how these fault arrays interact. By analysing a selection of end member conjugate fault relationships using quantitative analysis such as displacement-depth plots, we can determine relative timing of the second rift phase to during the Berriasian. The reactivation of large NE-SW trending Jurassic faults, which developed during the initial rift phase, could provide the framework to understanding the relationship and relative timing of these later Cretaceous conjugate faults.

This work forms part of a study that attempts to resolve the rift evolution of the Exmouth Sub-basin, and the local impact of faults on fluid flow. This is paramount to understanding the extensive petroleum system within the region.

## **Sliding of Faults Under Controlled Stress Conditions**

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Controlled stress path experiments were used to investigate sliding of non-optimally oriented faults, under constant normal stress and loading at constant confining pressure, with tests performed under both uniaxial compressive and extensional loading regimes. We also investigated the effects of varying pore pressure and adding fault gouges of varying compositions.

Tests were carried out on sandstone Pennant Sandstone (4% porosity). It is ideal on account of its due to its weak fabric, uniform composition, enough porosity to allow pore pressure tests whilst being sufficiently strong to avoid unwanted formation of fresh faults for many pre-cut fault orientations. Samples were cut at 35°, 45° and 55° to the long axis; others were fractured over a range of confining pressures so the natural fault angle could be determined.

Pre-cut samples were axisymmetrically compressed or extended using different load paths to determine whether different stress regimes could cause unfavourable fault angles to slide. In compression, the fresh fault angle was approximately 35° to  $\sigma_1$ , but only 18° in extension. Some samples were tested with continually varying pore pressure to allow the entire friction envelope to be mapped using a single specimen.

Friction coefficient in extension is systematically lower than in compression, implying intermediate principal stress influences frictional properties (as it does for intact rock failure), contrary to the predictions of Mohr-Coulomb theory. The influence of pore pressure is sensitive to whether granular fault gouge is present. Gouge allows pore pressure to be fully effective over the whole area of a fault, whereas in shear-oriented cracks it is not, but accesses such cracks by preferred flow along channels (fingering).

## **A tensorial approach for the quantification of fracture patterns in 3D**

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Fractures in rocks are rarely random. Fracture orientations, sizes, shapes and spatial distributions often exhibit some kind of pattern. This is important because the bulk mechanical (e.g. strength, elastic anisotropy) and bulk transport (e.g. fluids, heat) properties of rock depend on these patterns. This presentation describes an assessment of the crack tensor as a way of quantifying fracture patterns, including statistical distributions in fracture attributes and their spatial variation. Published formulations of the crack tensor include assumptions concerning the relationships between crack orientations and their sizes, and the spatial distributions of crack centres. This contribution explores these assumptions.

Data has been collected from 2D digital images of deformed rock and software scripts have been developed based on published numerical methods for the analysis of fracture attributes: orientations, lengths and shapes of fracture traces are measured and their distributions quantified. Fracture trace data from multiple 2D images can be combined using stereological principles to derive the statistically equivalent 3D fracture orientation distribution. The current focus for the application of the tensorial approach 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 in layered rocks, but fault zones in general present a bigger and arguably more important challenge. Better quantification of natural fractures and their patterns will enable more robust evaluation of predictive fracture models.

# **Geometrical and petrophysical properties of cataclastic deformation bands from contrasting sedimentary facies**

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The microstructure of deformation bands is known to vary as a function of clay mineral content and diagenetic effects occurring before or after deformation. It has been suggested that the original rock texture may also influence the microstructure and hydraulic properties of these commonly observed features. Grain size distributions (sorting), grain shape distributions (roundness, angularity), grain packing and mineralogy (compositional maturity) might also be important. In this contribution, we explore the role of sedimentary depositional environment on the geometry and petrophysics of cataclastic deformation bands.

We present a comparison of samples from a range of depositional environments including aeolian dune, shallow marine shoreface, deep marine channel and fluvial point bar. Preliminary evidence suggests that the conditions of deformation were broadly similar in each case, with normal fault kinematics and maximum burial depths  $< 3$  km. We present preliminary results of a petrographic and petrophysical analysis of oriented samples from each of these distinct sedimentary environments including: quantitative image analysis of optical and SEM micrographs; porosity and permeability data from core plugs; and ultrasonic P- and S-wave velocities from core plugs. We also provide a quantitative comparison of deformation band geometry in 2- and 3-D from field and laboratory measurements.



## **Evidences of synsedimentary tectonic activity in the Meso-Cenozoic apulian platform carbonates, southern Italy**

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Meso-Cenozoic platform carbonates, that stratigraphically overlie Triassic evaporates and late Paleozoic siliciclastic units, largely outcrop in the Murge Plateau and Gargano promontory, which represent two different foreland domains of the Apenninic orogenic belt in southern Italy. In the Murge Plateau stratigraphic succession performs inner platform carbonates, whereas in the Gargano Promontory a lateral transition from platform to slope and basin facies outcrops. Both in Gargano and Murge areas there were documented NW-SE striking normal faults and WNW-ESE, NNW-SSE strike-slip faults, right-lateral and left-lateral respectively, crosscutting Late Cretaceous shallow water and basin carbonates. These faults show some evidences of synsedimentary character, such as neptunian dykes, consisting of large clasts of breccia, clay material and calcite, and the variation of bed thickness in the hanging wall and footwall. Moreover, karst features often are present within the fault damage zones affecting shallow water carbonates in the Murge Plateau. The observed fault patterns and their overall kinematics allowed us to reconstruct, in both areas, the geometry of the stress field responsible for synsedimentary faults development.

## **Fault rock in carbonate-hosted normal fault zones**

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Predicting the sealing capacity of fault zones is rarely straight forward. The heterogeneity of carbonate fault rock textures increases the complexity of this task substantially. Sealing capacity is a function of the fault zone architecture and the deformation mechanisms active in the production of fault rocks in the fault core. Lithological variation in a faulted carbonate succession will lead to different deformation mechanisms, and this can generate a variety of fault rocks along a single slip surface. The porosity and permeability of the fault zone will therefore vary along strike and down dip on any single slip surface.

This study focuses on selected normal fault zones on the island of Malta. Fault displacements range from 0.52 m up to 90 m, and this allows us to investigate the systematic evolution of fault cores with displacement. A detailed examination of the along strike heterogeneity of the fault core in a single 60 m displacement fault has also been performed. Along one fault, the permeability of the fault rock can vary from 0.001mD to 80mD and the porosity can vary from 1.5% to 15%. Fault core zones should therefore not be thought of as a single low porosity, low permeability zone, but can be highly variable, and this variability is a function of the deformation mechanisms that produced the fault rock along the slip surface. A continuous fault core that could have been thought of as an effective seal/baffle may have areas of much higher permeability, causing the fault to leak.

## Recognition of fluid pressure fluctuation from quartz vein orientations – a study based on 3-D Mohr circle construction

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It is known that if fluid pressure ( $P_f$ )  $> \sigma_2$  then fractures/faults having various orientations get reactivated, and poles to dikes/veins show a girdle distribution on lower hemisphere equal area projection. Conversely, if  $P_f < \sigma_2$  then fractures/faults of a particular orientation tend to form/reactivate, thus resulting in a clustered distribution of poles to dikes/veins. This principle has been used previously to construct 3-D Mohr circle to analyze relative stress/ $P_f$  condition of dike/vein emplacement. In the present study, this approach is followed to analyze the quartz veins from the Archaean lode-gold bearing region of Gadag (southern India). Quartz veins have a wide range of orientations and show a girdle distribution. 3-D Mohr circle analysis indicates that the driving pressure ratio ( $R'$ ) was 0.94. However, despite the girdle distribution, a maximum is noted in the southwesterly direction. It is argued that when  $P_f > \sigma_2$ , fractures having various orientations formed/reactivated. This led to “burping” of fluid into the fractures, thus forming veins. During this fluid flow,  $P_f$  fell below  $\sigma_2$ , and fractures having NW-SE strike/easterly dip were susceptible for reactivation. This resulted in the cluster (maximum) of poles to veins in southwesterly direction. 3-D Mohr circle analysis reveals that when  $P_f < \sigma_2$ ,  $R'=0.07$ . Once these fractures were sealed by veins, permeability reduced, thus initiating the next cycle of rise in  $P_f$  to levels greater than  $\sigma_2$ . Based on the study it is therefore concluded that quartz veins in the Gadag region are a consequence of an interplay between conditions that fluctuated from  $P_f > \sigma_2$  to  $P_f < \sigma_2$ .

## **Lateral flow in the middle crust – Analogue experiments from the Svecofennian orogen**

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The exposed Svecofennian crust (50-65 km) has been suggested to have thickened in continental accretion between Archean and Paleoproterozoic terranes (Korja et al. 1993), probably at a high convergence rate. It is likely that this thickened orogen experienced lateral spreading during its final stages (Korja et al. 2009). This post-orogenic “collapse” must have reshaped the collisional framework and modified its bulk appearance. In this study, we have used scaled analogue centrifuge modeling to simulate this extensional lateral flow at the Archean- Paleoproterozoic boundary zone during final stages of the Svecofennian orogeny. The analogue models simulate both the evolution of a mechanical boundary between two rheologically different tectonic blocks, and the role of pre-existing faults cutting the model at moderate angles (representing the old stacking structures). The model results show that during extension the rheologically different layers deform and spread at different rates during the tectonic collapse resulting in; 1) vertical rotation of the boundary between the Archean and Proterozoic blocks; 2) modification of the pre-existed faults to become listric and discontinuous; and 3) the isostatic upward flow of the low viscosity middle layer to fill the gaps between the upper layer blocks. The experiments show geometrically similar crustal-scale structures to those observed in the deep seismic reflection profiles (FIRE).

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Korja, A., Korja, T., Luosto, U., & Heikkinen, P. (1993). Seismic and geoelectric evidence for collisional and extensional events in the fennoscandian shield implications for precambrian crustal evolution. *Tectonophysics*, 219(1-3), 129-152.

Korja, A., Kosunen, P., & Heikkinen, P. (2009). A case study of lateral spreading: The Precambrian svecofennian orogen. *Geological Society, London, Special Publications*, 321(1), 225-251.

## **Strain analysis of the Greater Himalayan Sequence, Central Nepal: A method to test the channel flow hypothesis**

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The channel flow hypothesis for the Himalayan orogen suggests that the Greater Himalaya Sequence (GHS) represents a partially molten, mid-crustal channel bound by ductile shear zones. The predicted vertical distribution of strain across the GHS is one aspect that is yet to be fully investigated. A methodology to address this issue is described herein. A new geological map for the Annapurna-Dhaulagiri Himal of central Nepal is presented, produced from previously published data combined with new structural data and 93 sample locations collected during recent fieldwork in the region. Microstructural analysis of these samples will be used to examine the vertical distribution of strain across the GHS and bounding units. The outlined methodology will utilise a variety of techniques to quantify and characterise strain within these samples. SEM electron back scattered diffraction (EBSD) will be used to measure the crystallographic preferred orientation of individual mineral phases of these samples, providing valuable information on deformation mechanisms and a proxy for strain. Anisotropy of magnetic susceptibility (AMS) will be used to provide a proxy for strain in samples that are too heterogeneous for EBSD. Additional strain and vorticity data will also be collected via optical microscopy. The resulting data set will be used to determine a vertical strain profile for the Himalayan orogeny. This will be coupled with existing geochronometric and thermobarometric data to determine the kinematics of the Greater Himalayan Sequence, thus providing a means to critically assess the strain distribution predicted by current channel flow models for the Himalayan orogen.

# **Characterizing the Holocene slip history of active normal faults: an integrated study using terrestrial laser scanning, ground penetrating radar, $^{36}\text{Cl}$ cosmogenic exposure dating and field analysis**

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Cosmogenic exposure dating is increasingly being used to model fault slip histories on exhumed bedrock scarps produced by active normal faults. A critical yet overlooked component of the methodology is a robust understanding of the complex tectono-geomorphic evolution of the sample site. Such an approach is critical because a cosmogenic exposure age is only as good as its site characterisation. Therefore, in order to produce seismic hazard assessments or analyse fault interaction we must ensure that robust millennial slip histories are derived. Central to this is conformation that the sampled bedrock scarp is the result of the rupture process only, and does not reflect modification by additional surface processes such as erosion. Here we present an integrated tectono-geomorphic study of bedrock fault scarps in Abruzzo, Central Italy, and show that site characterisation is key to interpreting  $^{36}\text{Cl}$  cosmogenic exposure ages in terms of fault slip history.

We quantify surface modification of the footwall, hangingwall and scarp using detailed terrestrial laser scanning (TLS), combined with ground penetrating radar (GPR) analysis of the hangingwall sedimentation. Having identified and characterized sites exhumed only by the rupture process, we show that the concentration of cosmogenic  $^{36}\text{Cl}$ , both in the subsurface and along the subaerial portion of the scarp, varies systematically as a function of fault slip rate. The slip rates that we derive compare well with independent estimates of average Holocene rates and to slip rates inferred from along-strike paleoseismological investigations of the same structures.

We conclude that this type of integrated approach is necessary in order to derive internally consistent estimates of fault slip rates over different time scales that can (a) provide more robust parameters to inform regional seismic hazard analysis, and (b) improve our understanding of the mechanisms that control slip rate variability.

## **Controls on and Timing of Hydrothermal Vent Formation in the Exmouth Sub-basin, Offshore NW Australia**

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Fluid flow in the subsurface is strongly influenced by the pre-existing structure of the upper crust as well as the emplacement of magma intrusions. Sedimentary basins developed along volcanic margins often contain hydrothermal vent-complexes generated by intrusion-induced hydrothermal activity and these complexes may be used to relatively date magmatic activity. While several studies describe a spatial association between lateral sill tips or faults and vent distribution, mechanisms controlling fluid flow along fault-planes remains poorly understood.

Here, we use 3D seismic reflection data from the Exmouth sub-basin (offshore NW Australia) to study the structure of a hydrothermal vent-complex and its relationship to faults. The Exmouth sub-basin has been influenced by two phases of extension; large NE-SW trending normal faults formed in the Toarcian following the breakup of Argo-land from India and closely spaced, conjugate normal faults were developed during rifting between Greater India and Australia in the Berriasian.

We investigate the role that the Toarcian faults played in feeding the hydrothermal vents through detailed mapping and construction of displacement-depth plots to constrain the relative age relationships. We find the vents typically have an ‘eye-shaped’ structure and are occasionally aligned, perhaps along normal fault strike. Identification of Late Jurassic seismic reflections that onlap onto the vents indicate extrusion occurred in the Early Tithonian. This work provides important information on the fluid flow pathways within the Exmouth sub-basin that influence subsequent magmatic and petroleum systems.

## **Distributed Late Miocene normal faulting beneath the northern Nile Delta: NNW propagation of the Gulf of Suez Rift**

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The Nile Delta lies on the North African-Levant “passive” continental margin. Here we present evidence of one tectonic episode which has interrupted the thermal subsidence phase of this margin. Structural interpretation has been carried out on a grid of thirty 2D seismic reflection profiles covering the onshore and offshore of the north central part of the Nile Delta. Syn-depositional normal faults have been indentified throughout the study area with a predominant strike of NNW-SSE, buried beneath the Pliocene-Quaternary succession of the Nile Delta. Well data tied to the seismic interpretation allow the lithostratigraphic sedimentary succession beneath the north central part of the Nile Delta to be divided into tectonic megasequences with respect to this event. The pre-rift megasequence culminates in the upper part of the Sidi Salem Formation (Serravallian-Tortonian age), a syn-rift megasequence comprises the Qawassim Formation (Tortonian) and the Abu Madi Formation (Messinian age), and a post-rift megasequence is first represented by the Kafr El-Sheikh Formation (Lower-Middle Pliocene age). Characteristic stratal dip fans with onlap onto hangingwall dipslopes define the syn-rift. Faults and associated hangingwall depocentres and zones of footwall uplift have lengths of up to about 8-10 km. The Qawassim and Abu Madi Formations are separated by a prominent unconformity which correlates with the Messinian drawdown event.

Red Sea and Gulf of Suez rifting propagated to the NNW through the Oligocene and Miocene. Current spatial relationships of continental rifting in the NNW compared to oceanic rifting in the SSE thus represent the temporal evolution of rifting. The study area under the north central Nile Delta extends the expression of continental rifting NNW from the Gulf of Suez, as a zone of distributed smaller-scale normal faulting which is the precursor to the development of larger-scale, hard-linked, rift-bounding fault sets as seen in the Gulf of Suez. The NNW-SSE normal faulting thus represents the early stage northward propagation of Gulf of Suez rifting in the Late Miocene (Messinian).



## **Subsurface investigation of the Pre-Oxfordian tectonic evolution of the Exmouth Sub-basin offshore NW Australia**

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The Exmouth Sub-basin formed as part of a series of northwest-southeast trending basins due to a series of tectonic events during the Pliensbachian to Oxfordian. The basin has since undergone further extension in the Valangian and Hauterivian, however the geology of the basin and the interaction between rift episodes is poorly understood.

This study investigates the effect of multiphase rifting on fault syn-rift sedimentation as well as fault reactivation and geometry. We use 3D seismic reflection data to map a network of normal faults; the development of which significantly influences contemporaneous sedimentation. The identification of these thickness variations plays a key role in determining basin evolution and potential implications to its hydrocarbon systems.

We suggest that stress field variations, caused by a series of pre-Oxfordian rifting and inversion events, have resulted in a complex fault network. Later, post-Oxfordian tectonic events have provided suitable conditions for fault reactivation and resulted in the modification of fault geometry.

This work emphasizes the importance of a structural network in the evolution of a continental rift and provides important information on the migration and trapping of hydrocarbons.

## **Spatial characterisation of fracture systems: a comprehensive global database of fully-attributed multi-scale fracture data**

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Fractures play a fundamental role in controlling reservoir quality and performance in a large proportion of carbonate and basement reservoirs and some clastic reservoirs.

Fracture characterization is complex, time consuming and expensive. Because of this, geologists and engineers often cannot rely on asset-specific studies and have to use analogue data. However, the large number of variables affecting fracture propagation, initiation and development mean that obtaining reliable fracture analogue data is difficult.

To address this problem data have been collected from public domain datasets, research group datasets, FRL multi-client data, field work, FMI, and core logging at a range of scales – from micro-structural analysis to kilometre long fissures to create ERGO Fractures; a unique online system designed to provide analogue fracture data and information to support fracture modelling. Detailed fracture data have been collected including fracture continuity, dimensions (length, width, aperture), orientations, frequencies and densities. The fracture data has been attributed with lithology, tectonic setting and linked to deformation events to allow data from different regions to be compared. To aid understanding of the effect of fractures on reservoir performance, the data can be filtered and statistically analysed to describe orientation trends, identify length/aperture relationships and estimate fracture frequencies and densities. ERGO Fractures also includes a comprehensive knowledgebase that provides information concerning classification, distribution, initiation and propagation, and the controls on fracture networks. Fracture modelling requires the user to input a number of fracture properties including aperture, length, shape, size and tools created specifically for the ERGO Fractures database allow the user to generate cross-plots (e.g. length vs aperture) to evaluate the numerous fracture relationships, and to view fracture data presented in a number of forms including intuitive stereonet, rose diagrams and cumulative frequency plots.

## **Thermal modelling of the Makran Subduction Zone and relationship to past and future seismicity**

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The Makran Subduction Zone is a global end-member among subduction zones due to its shallow dip and wide (>200 km) accretionary prism. This margin experienced an  $M_w$  8.1 potential plate boundary earthquake in 1945 which generated a damaging tsunami and killed over 4000 people. With the exception of the 1945 event, seismicity in the Makran is relatively low when compared to other global subduction zones, however some seismicity is observed in the shallow part of the megathrust. To further understand the seismogenic potential of this margin 2D thermal modelling was undertaken of the subducting plate, producing a thermal profile of the subduction zone, and generating an estimate of surface heat flow. The geometry of the model is constructed from seismic reflection data, seismicity where present, and the position of the volcanic arc. The primary results from the thermal modelling are twofold. 1) The thick sediment cover on the incoming oceanic plate leads to high ( $\sim 150^\circ$ ) plate boundary temperatures at the deformation front, and 2) The shallow dip of the subducting plate (and so shallow dip of the thermal contours) leads to a wide potential seismogenic zone. These results demonstrate the potential for the Makran to produce shallow plate boundary earthquakes of  $M8.5^+$ , a hazard not previously acknowledged for the surrounding region.

## **Digital Geological Mapping – A solution to a problem or a natural evolution?**

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Field mapping is used to gather geological data for construction of models and analysis. The data gathering has traditionally been undertaken on paper maps with the geologist noting down personal observations directly onto a map and additional notes being recorded in a field notebook. This information, typically recorded in pencil, would be required to be 'inked in' in the evening to ensure there was a fair copy of the data for analysis at a later date.

With increased performance capabilities and reduced price of hardware, electronic devices have become more attractive for use with mapping. GPS devices were used to improve the accuracy of locality information, often having to be used in conjunction with a paper map where the data was recorded. Digital cameras meant that a geologist could take as many photographs as they wanted and use/reject them as they please when reviewing the data, reducing the reliance on field sketches.

However increased portability of electronic devices, has led to the development of programs like Midland Valley's *FieldMove* application. The ability to use built in devices to record location information and data has dramatically improved the efficiency of the field geologist, allowing more time for thinking about the geology. Data captured in *FieldMove* can also be imported directly into *Move* where the user has access to a wide range of tools for cross-section construction and 3D model building allowing geometrically plausible models to be built rapidly during the field campaign.

## **Paleoproterozoic nappe stacking in the Rwenzori Mountains, East African Rift System**

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The Rwenzori Mountains resemble an uplifted horst block that lies within the western part of the East African Rift System (EARS). Even though the recent uplift of this basement block is young, it actually resembles a much older fold and thrust belt made up of Archaean basement gneisses and Paleoproterozoic sediments and volcanics. Recent observations suggest that this Proterozoic fold and thrust belt resembles a northwards thrust sequence of thick skinned imbricates (Link et al., 2010). The high peaks of the Rwenzori Mountains are made up of the frontal part of this belt. Here a sequence of Paleoproterozoic sediments and amphibolites overlie Archaean basement gneisses and are themselves overlain by the second Archaean gneiss thrust sheet. The metamorphic grade that is observable in schists within the Paleoproterozoic sediments of the high Rwenzori sequence show an overturned metamorphic sequence with schists in the lower units having Greenshist facies and the schists in the higher units Amphibolite facies metamorphism. Deformation shows a dominant thrusting towards the north at the same time as the peak metamorphism. Here we present a detailed microstructural and petrological analysis of the Paleoproterozoic units of the high Rwenzoris in order to understand the exact nature of the fold and thrust belt.

Link, K., Koehn, D., Barth, M., Tiberindwa, J., Barifaijo, E., Aanyu, K., and Foley, S., 2010, Continuous cratonic crust between the Congo and Tanzania blocks in western Uganda: International Journal of Earth Sciences, v. 99, p. 1559-1573.

## **Late Cenozoic uplift of the Canadian Rocky Mountains**

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As part of the North American Cordillera the Rocky Mountains of Canada influence climate on a local and global scale by deflection of weather systems and the jet stream, and the formation of a distinct barrier to Pacific moisture to the continental interior. The extent to which this climatic pattern extended into the past is at present uncertain, so knowing the elevation history of the Rockies is critical to understanding what the controls on Northern Hemisphere climate change comprise. The Cordillera comprises a deformed continental margin and further west multiple amalgamated terranes accreted during Jura-Cretaceous time following eastward subduction of ocean crust. After contraction ended in latest Cretaceous time, a phase of extension during the Paleocene-Eocene formed multiple core complexes, thinned the crust and moved segments in a dextral fashion by strike slip faulting. In the Neogene, plateau basaltic volcanism was prominent and was followed by the rise of Coast Mountains. What is unknown is the time of rise of the currently conspicuous Rocky Mountains on the east side of the orogen, and the effect of this on Cenozoic climate. This project investigates the mid-late Cenozoic uplift history of the Rocky Mountains using low temperature thermochronology from Apatite- and Zircon-Helium dating and Apatite Fission Track dating. Preliminary results from the thermochronology are presented which illustrate the varied patterns of uplift across the region. When combined with thermal modelling this will provide insight into the detailed uplift history and allow for conclusions regarding the driving tectonic forces.

## **Structural and lithological controls on the northern margin of the Tibetan Plateau**

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The Qilian Mountains and Qaidam Basin, northeast Tibet, form the youngest part of the Tibetan Plateau, and may provide a type example for the evolution of older regions of the Plateau. The area is a reactivated orogenic suture belt which was accreted to the North China Craton during the mid-Palaeozoic. Deformation and mountain building associated with the Indo-Asian collision have been active in the region since the Miocene and are characterised by the formation of fold-thrust ranges which splay southeastwards from the sinistral northeast trending Altyn Tagh Fault (ATF). This study will investigate both the Quaternary and Pre-Quaternary tectonics around the Changma Basin at the very northeastern corner of the Plateau. Here the ATF forms a triple junction with the frontal thrust of the Qilian Nan Shan range. The basin is surrounded on all sides by high mountain ranges composed of lower Palaeozoic meta-sedimentary and meta-volcanic rocks, which are being actively uplifted either by frontal thrusts or transpression along the ATF. By linking structural transect mapping, remote sensing and image analysis, the structures and lithologies within the ranges are being documented to establish the extent of basement control on the modern growth of the mountain ranges and on the kinematics of the faults responsible for their uplift. These new data will be used to test the hypothesis that the northeastward growth of the Tibetan Plateau is constrained by pre-existing weaknesses in the Palaeozoic crust to the south of the ATF and rigid Archaean basement to the north.

## **Strain distribution at depth within continental strike-slip fault zones: an example from the Karakoram Fault Zone, NW Himalaya**

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Knowledge of the distribution of strain at depth within continental strike-slip fault zones is a significant factor in understanding the seismicity and evolution of such faults and their role in continental deformation. In active fault zones the strain distribution in the ductile component is difficult to constrain. However, information on the strain distribution, kinematics and conditions of deformation at depth can be derived from analysis of crystallographic preferred orientations (CPO) within exhumed ductile fault rocks.

Electron Backscatter Diffraction analysis of CPO in samples from transects across the multi-stranded Karakoram Fault Zone (KFZ), a major 800-km-long dextral strike-slip fault bounding western Tibet, has been used to assess the distribution of deformation across the fault. CPO analysis indicates that the deformation occurred at up to lower amphibolite facies. Quartz CPO strength provides a proxy for strain variation between samples and is quantified using the J-index for the bulk fabric along with pfJ and the eigenvector derived strength parameter for both *c*- and *a*-axes pole figures. Results from five granitoid plutons in the vicinity of the KFZ show that strain is localised within a <2880 m wide zone displaying marked cross-fault asymmetry. Strong strain gradients from mylonitic (strong CPO) to undeformed (no CPO) in 16 Ma and 17 Ma plutons suggest that the KFZ initiated after ~16 Ma (i.e. is not synkinematic with leucogranite intrusion) and is a relatively short-lived structure within the Himalayan-Tibetan orogen.



## **Reconstructing geometries of the Achnashellach Culmination using forward modelling algorithms in Move**

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Multi-stage thrusting during the formation of the Achnashellach Culmination, southern Moine Thrust belt, has been identified by detailed mapping and field relationships of structures. Cross sections have been constructed based on data collected in the field which illustrate geometries in this fold-and-thrust belt. Here we test different methods of forward modelling in Move software in order to reconstruct the cross sections to give accurate geometries and to understand the evolution of the area.

Different move on fault algorithms within Move create a range of fold geometries and influence the strain distribution throughout the folds. In order to recreate fold geometries it is necessary to use a combination of deformation algorithms including fault parallel flow and trishear.

This forward modelling reveals how strain within the Torridonian Sandstone and overlying Cambrian sediments may have evolved through time and allows identification of potential high strain zones where fracture densities are likely to be highest.

## **A multi-disciplinary approach to refining plate tectonic models: Examples from the Arctic**

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Plate tectonic reconstructions provide an important framework for a variety of geologic studies. Developing such reconstructions requires evaluation and integration of several geodynamic and geophysical data sources, including tectonic regimes, plate boundary interpretations and palaeomagnetism. We present a multi-disciplinary approach to plate modelling which integrates structural mapping based upon potential field data, seismic data and palaeoenvironmental interpretations. Tectonic solutions are then developed and refined using feedback from sources such as palaeogeography, palaeotopography and palaeobathymetry whilst still satisfying geological and geophysical constraints. .

Our global plate model comprises Jurassic to present day plate reconstructions. Major continental blocks have also been reconstructed to the Neoproterozoic using published palaeomagnetic constraints, fossil distributions and geodynamical arguments. We are currently extending the global model to include Permo-Triassic reconstructions, using structural interpretations of major fault systems, potential field data and geological relationships. Here we focus on model developments in the Arctic realm, where tectonic evolution is notably complex. Using examples from the Russian Arctic and the North American Cordillera we demonstrate the methodology and potential applications of our plate reconstructions.

In the Arctic region, major faults including the Border Ranges Fault and the Tintina Fault in North America and the Verkhoyansk Fold and Thrust Belt and the Chersky Collision Belt in the Russian Arctic define unique tectonic units. Motion on these faults is used to constrain relative motions between tectonic units. We also use palaeogeography and palaeomagnetism studies to understand and refine the evolution of allochthonous terranes, the origins of which remain heavily debated.

## **Outcrop Analogue Derived Synthetic Seismic Data: A Tool for Understanding Rift Scale Structural Uncertainty**

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Much of our understanding of sub-surface rift structure is derived from 2D seismic sections, with 3D coverage generally being restricted to localised areas. Constraining the along strike variation in geometry hence relies on correlating between often widely spaced sections. This results in significant uncertainty in fault displacement distribution and the location and geometry of fault linkages. In turn this limits the degree to which we can constrain 3D rift evolution. Synthetic 2D seismic sections across known outcrop geometries allow us to capture and visualise structural uncertainty in a 3D context. This provides us with a useful tool for understanding the limitations and uncertainties of 2D data.

Detailed field mapping and structural data collection has allowed construction of a 3D geological model of the onshore Gulf of Corinth rift, with fault- and fault-linkage geometries being relatively well constrained. Sample analysis combined with published depth trends have allowed the model to be populated with petrophysical properties appropriate for sub-surface burial conditions. Seismic forward modelling software is used to generate synthetic sections at intervals typical of exploration scale seismic acquisition. Comparison of the synthetic sections with the mapped 3D geometry allows us to constrain the potential uncertainty when predicting 3D rift configuration from 2D data. This work has applications both as a teaching tool and within the hydrocarbon industry, where the inherent limitations of 2D data leads to significant uncertainty in the depth and location of spill points, and hence in potential hydrocarbon column heights and volumes.

## **Geological History of Britain and Ireland: 2nd edition**

Edited by Nigel Woodcock and Rob Strachan

Britain and Ireland have a remarkably varied geology for so small a fragment of continental crust, with a fine rock record back through three billion years of geological time. This history would have been interesting enough if it had been played out on relatively stable continental crust. However, Britain and Ireland have developed at a tectonic crossroads, on crust once traversed by subduction zones and volcanic arcs, continental rifts and mountain belts. The resulting complexity is instructive, fascinating and perplexing.

Geological History of Britain and Ireland tells the region's story at a level accessible to undergraduate geologists, as well as to postgraduates, professionals or informed amateurs. This second edition is fully revised and updated, reflecting continually developing knowledge of the region's geology. Full coverage is again given to the rich Precambrian and Early Palaeozoic history, as well as to later events more relevant to hydrocarbon exploration. The book is an essential starting point for more detailed studies of the regional geology.

The team of authors (below) has been augmented for the second edition, to ensure that every aspect of British and Irish history is authoritatively covered. The structural expertise of the team and of the editors ensures that tectonic geology is given its proper place in this story

Roger Anderton  
Sarah Davies  
Andy Gale  
Phil Gibbard  
Paul Guion

Pete Gutteridge  
Steve Hesselbo  
Bob Holdsworth  
Mark Hounslow  
Tom McKie  
Tony Prave

Alastair Ruffell  
Craig Storey  
Rob Strachan  
Laurence Warr  
Nigel Woodcock