

# Tectonic Studies Group annual general meeting 2007

## University of Glasgow



Organising committee:  
*Clare Bond and Zoe Shipton*

Thanks to the following people for help:  
*Emma Boyle, Neil Burnside, Cristina Persano  
Jamie Kirkpatrick, Aisling Soden, Geoff Tanner*

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# TSG 2007 Programme

**Tuesday 2<sup>nd</sup> January** 18.30-19.30 Registration desk open at Sandyford Hotel

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## **Wednesday 3<sup>rd</sup> January**

9:00-10:50 Registration & poster set-up

10:00-10:50 Coffee and tea in the Reading Room

### **Session 1. Chair: Cristina Persano**

10:50 Meeting opens

11:00 Rock deformation processes in the Karakoram fault zone, Eastern Karakoram, Ladakh, NW India. *Ernest H. Rutter, Daniel R. Faulkner, Katharine H. Brodie and Richard J. Phillips, Michael P. Searle*

11:15 Structural evolution of the South Tibetan Detachment System and its implications for exhumation of the High Himalaya. *John M. Cottle, Micah J. Jessup, Dennis L. Newell, Michael P. Searle and Richard D. Law*

11:30 Using inclusion trails to refine P-T-d paths in the Rodinian LP/HT terrane of the Mount Isa window, Australia. *Mohammed Sayab*

11:45 Distribution, chronology and causes of Cenozoic exhumation in the southern British Isles. *Simon P. Holford, Jonathan P. Turner, Richard R. Hillis, Paul F. Green, Anthony G. Dore, Robert W. Gatliff, Martyn S. Stoker, Kenneth Thomson, John R. Underhill and Gareth A. Williams*

12:00 The unroofing of an orogen. *Tim Dempster, Liam Reinhardt, Stewart Clark and Cristina Persano*

12:15 Arabia-Eurasia collision: multiple causes of Oligocene global climate cooling? *Mark Allen and Howard Armstrong*

12:30-13:30 Poster session and lunch

### **Session 2. Chair: Mats Schöpfer**

13:30 Investigating the relationship between fault permeability, pore pressure and effective stress using constraints from reservoir induced seismicity. *Rebecca J. Lunn, Aderson F. do Nascimento, Zoe K. Sipton, Patience A. Cowie*

13:45 Predicting fracture and porosity evolution in dolostone. *Julia F. W. Gale, Robert H. Lander and Robert M. Reed*

14:00 Footwall extension during low- angle normal faulting: controls on fault zone structure and fluid flow. *Steven A. F. Smith, Robert E. Holdsworth, Cristiano Collettini and Jonathan Imber*

14:15 On the origin and distribution of fracture damage surrounding strike-slip fault zones: implications for fluid flow. *Tom M. Mitchell and Daniel R. Faulkner*

- 14:30 On the formation of and fluid pressure within strike-slip dilatational jogs: constraints on crustal stresses at depth. *J. Cembrano, Daniel R. Faulkner, V. Herrera and Tom M. Mitchell*
- 14:45 How strong is the Alpine Fault? Evidence from fluid flow and deformation partitioning in the Pacific Plate hanging-wall, New Zealand. *Ruth H. Wightman and Timothy A. Little*

15:00-15:45 Poster session with coffee and tea

### **Session 3. Chair: Ruth Wightman**

- 15:45 Normal growth fault evolution in the Columbus Basin, Trinidad. *Ulrike A. Freitag, David J. Sanderson and Lidia Loneragan*
- 16:00 Growth of normal faults during rift-raft tectonics; evidence from 3D seismic and well data, South Viking Graben, Quad 15/3. *Christopher A-L Jackson and Eirik Larsen*
- 16:15 Controls and timing of structural inversion in the NE Atlantic Margin. *Adrian Tuitt, John Underhill, Roger Scrutton, Derek Ritchie, Howard Johnson and Ken Hitchen*
- 16:30 Structural style of Malague fold-and-thrust belt at the Rio Diamante area, Mendoza province, Argentina. *Martin M. Turienzo and Luis V. Dimieri*
- 16:45 Variation in deformation style within a fold-thrust belt. *Caroline M. Setchell, John W. Cosgrove, David Cannon and Terry Engelder*

17:00-19:00 Poster session with wine reception (sponsored by Statoil)

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## **Thursday 4th January**

### **Session 4. Chair: Julia Gale**

- 9:00 Fracture zone orientations onshore Faroe Islands (North Atlantic); evidence for dual rifting episodes? *Heri Ziska, Marit Mortensen and John Zachariassen*
- 9:15 Recent tectonics of Outer Carpathians based on fractured clasts (first results). *Antek K. Torkaski, Anna Swierczewska, Witold Zuchiewicz and Nguyen Q. Cuong*
- 9:30 Fracture patterns in thrust-related anticlines: case histories from the Apennines, Pyrenees and Zagros thrust-fold belts. *Stefano Tavani, Fabrizio Storti, Francesco Salvini*
- 9:45 The kinematic history of the Khlong and Ranong faults, southern Thailand. *Ian Watkinson, Chris Elders and Robert Hall*
- 10:00 How to constrain the fault activity history of individual faults on timescales of thousands to millions of years. *Jonathan M. Bull, Philip M. Barnes, Geoffroy Lamarche, David J. Sanderson and Patience A. Cowie*
- 10:15 Plate boundary localisation in  $<10^5$  years from  $^{234}\text{U}$ - $^{230}\text{Th}$  dates from the 1981 earthquake fault, Greece. *S. L. Houghton, G. P. Roberts, C. Underwood, J. M. McArthur, I. Papanikolaou, P. van Calsteren and F. Cooper*

10:30-11:00 Poster session with coffee and tea

**Session 5. Chair: Martin Casey**

- 11:00 Mechanical and structural control on aftershock rupture planes. *Cristiano Colletini and Fabio Trippetta*
- 11:15 Evaporite bearing faults as a tool to understand the deformation processes into the seismogenic zone of the Northern Apennines, Italy. *Nicola De Paola, Fabio Trippetta and Cristiano Colletini*
- 11:30 Source mechanisms of acoustic emissions in triaxially loaded granite. *Caroline C. Graham, Sergi Stanchits and Ian G. Main*
- 11:45 The structure of an exhumed seismogenic fault: Sierra Nevada, California. *James D. Kirkpatrick and Zoe. K. Shipton*
- 12:00 Application of airborne LiDAR to mapping seismogenic faults in forested mountainous terrain, southeastern Alps, Slovenia. *Dickson Cunningham, Stephen Grebby, Kevin Tansey, Andrej Gosar, and Vanja Kastelic*
- 12:15 Characterization of normal fault curvature. *Timothy Wright and Jonathan Turner*

12:30-13:30 Poster session and lunch

**Session 6. Chair: Dave Prior**

- 13:30 Experimental determination of yield parameters for a high porosity sandstone. *Claire Glover, Ernie Rutter, Chidi Chukwunweike and Craig Ludlow*
- 13:45 Shear bands and fracture systems in granular materials - A numerical study. *Alison Ord, Bruce E. Hobbs and Klaus Regenauer-Lieb*
- 14:00 Kinematics and microstructural development of a high grade shear zone, Lewisian Gneiss, NW Scotland. *Mark A. Pearce, John Wheeler and David J. Prior*
- 14:15 Experimental dehydration of serpentinites: effects on mechanical behaviour. *Sergio Llana-Fúnez, Ernie Rutter and Kate Brodie*
- 14:30 Deformation of the Earth's lower mantle: insights from analogue materials. *Julian Mecklenburgh*
- 14:45 Dual petrological and strain-path controls on the seismic anisotropy of deformed continental crust. *Geoffrey E. Lloyd, Robert W. H. Butler, Martin Casey, J-Michael Kendall and Jennifer Halliday*

15:00-15:30 Coffee and tea in Reading Room (no poster session)

**Session 7. Chair: John Ramsay**

- 15:30 Faulting in non-plane strain: transtension in the Coso region, California. *John F. Dewey and Tatia Taylor*
- 15:45 Extrusion and vorticity. *Martin Casey*

- 16:00 The extension discrepancy at non-volcanic margins: depth-dependent stretching or unrecognised faulting? *Tim Reston*
- 16:15 Strain estimation from fault-slip data. *Richard J. Lisle, Atsushi Yamaji and Katsushi Sato*
- 16:30 How is extension distributed in the upper crust? *Martin W. Putz and David J. Sanderson*
- 16:45 **TSG Annual General Meeting**
- 17:30-18:00 **Plenary lecture:** Anatomy of an ancient earthquake from an exhumed fault. *Giulio Di Toro and Stefan Nielsen*
- 19:00 **Conference Dinner** (whisky sponsored by Midland Valley)

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## Friday 5th January

### Session 8. Chair: John Dewey

- 9:00 So what does the Moine Thrust actually do? Correlating the Torridon and Morar groups across the Moine Thrust, NW Scotland. *Maarten Krabbendam, David Cheer and Tony Prave*
- 9:15 Importance of multi-phase thrusting for tectonic reconstruction: Late Mesozoic – Early Cenozoic of Central Tauride Mountains, S Turkey. *Peter W. Mackintosh and Alastair H. F. Robertson*
- 9:30 Thrusts, mullions and culminations in the Moine rocks of south-west Sutherland, Scottish Caledonides. *A. Graham Leslie, Maarten Krabbendam and Rob A. Strachan*
- 9:45 Structural style of the eastern Kalachitta range, lesser Himalayans, N. Pakistan. *Shah Faisal, M. Asif Khan and Iftikhar Ahmad Abbasi*
- 10:00 A Rheic cause for the Acadian deformation in Europe. *Nigel Woodcock, Jack Soper and Rob Strachan*
- 10:15 Alternative tectonic models for the Late Cenozoic evolution of Cyprus: new evidence from the southern part of Cyprus. *Timothy C. Kinnaird, Alastair H. F. Robertson and Ionnis Panayides*
- 10:30-11:00 Poster session with coffee and tea

### Session 9. Chair: Christopher Jackson

- 11:00 A model for the structure and origin of mud volcano craters: examples from eastern Azerbaijan and the South Caspian Sea. *Robert Evans, Simon Stewart and Richard Davies*
- 11:15 Intrusive domain of the Koturdag mud volcano system, Azerbaijan. *Simon Stewart, Robert Evans and Richard Davies*

- 11:30 Potash values show Hormuz Island (Iran) to be a salt mushroom. *Pedram Aftabi, Christopher J. Talbot and Zurab Chemia*
- 11:45 Numerical modelling of rise and fall of dense layers in salt diapirs. *Zurab Chemia and H. Schmeling*
- 12:00 3D seismic imaging of a Tertiary dyke swarm in the southern North Sea. *Mostyn Wall, Joe Cartwright, Richard Davies and Andy McGrandle*
- 12:15 Depositionally-limited gravity-driven thrust tectonics from deep water South Africa. *Rob Butler, Richard Morgan, and Bill McCaffrey.*
- 12:30-13:30 Poster session and lunch

### **Session 10. Chair: Patience Cowie**

- 13:30 Archaeoseismology: a logical approach. *Iain Stewart, Manuel Sintubin, Dominique Similox-Tohon and Victoria Buck*
- 13:45 The systematic treatment of uncertainties in archaeoseismology. A proof of concept at the ancient city of Sagalassos (SW Turkey). *Manuel Sintubin, Iain Stewart and Dominique Similox-Tohon*
- 14:00 Geometry and deformation mechanisms of normal faults in the Nukhul half-graben, Suez rift, Egypt. *Paul Wilson, Franklin Rarity, David Hodgetts and Rob L. Gawthorpe*
- 14:15 Folding attached to hangingwall cut-offs of normal faults. *David J. Sanderson and Ulrike Freitag*
- 14:30 Brittle fault pattern along the Campbell Fault, a major right-lateral strike-slip fault system in northern Victoria Land, Antarctica. *Fabrizio Balsamo, Fabrizio Storti and Francesco Salvini*
- 14:45 Physical modelling of basement controlled normal faulting in wedge-shaped cover sequences. *Martin Schöpfer, Hemin Koyi, Conrad Childs, John Walsh and Tom Manzocchi*
- 15:00 Close meeting

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## **Saturday 6th January**

### **Short Courses and Workshops**

- 9:30-12:30 Structural interpretation from borehole images. Mark Lawrence, Baker Atlas Geoscience (room 311/312, East Quadrangle)
- 12:30-13:30 Lunch break (sponsored by Baker Atlas)
- 14:00-17:30 Structural workflows in the oil and gas industry. John Grocott, Midland Valley Exploration (Midland Valley offices – 144 West George St., Glasgow, G2 2HG)

## **Abstracts: Oral presentations (in order of presentation)**

## **Rock deformation processes in the Karakoram fault zone, Eastern Karakoram, Ladakh, NW India.**

Ernest H. Rutter\*, Daniel R. Faulkner<sup>1</sup>, Katharine H. Brodie

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Richard J. Phillips<sup>2</sup>, Michael P. Searle

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The Karakoram fault shows a full range of fault rocks from ductile (deformation by intracrystalline plasticity) mylonites to low temperature brittle fault rocks along the trace of the fault in the Eastern Karakoram, Ladakh, NW India. The Karakoram fault is a prominent feature on satellite images and has an estimated long-term average slip rate of 3 - 10 mm/yr, based on U-Pb geochronology of mapped offset markers. Mylonitic marbles, superimposed by cataclastic deformation and clay-bearing fault gouges and fracturing were found on a presently active strand of the fault, and testify to progressive deformation from plastic through brittle deformation during unroofing and cooling. From microstructural analysis we confirm the right-lateral strike slip character of the fault, estimate a peak differential stresses of ca. 200 MPa at the transition from plastic to brittle deformation, and found microstructural features to be consistent with inferences from the extrapolation of deformation behaviour from experimental rock deformation studies. Implied long term slip rates in the fault zone were estimated to be on the order of 3 to 10mm/a. Further northwest we found tourmaline plus quartz-bearing veins that are either replacements of frictional melt-glass or more likely original pneumatolytic fault breccias that formed early in the history of the fault and are probably older than 10 Ma.



## **Structural evolution of the South Tibetan detachment system and its implications for exhumation of the High Himalaya.**

John M. Cottle<sup>\*1</sup>, Micah J. Jessup<sup>2</sup>, Dennis L. Newell<sup>3</sup>, Michael P. Searle<sup>1</sup> Richard D. Law<sup>2</sup>

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Current models for exhumation of the High Himalaya invoke a Channel flow mechanism whereby a channel of low viscosity material (the Greater Himalaya Series (GHS)) is extruded from mid-crustal depths southward from beneath Tibet. Critical to testing Channel Flow models and understanding the exhumation of the GHS is a detailed knowledge of the bounding structures of this system. This study focuses on the tectonic feature defining the top of the slab - the South Tibetan Detachment System (STDS). Here we present new field, petrological, thermobarometric and geochronological data from three transects spanning ~100km strike length of the STDS that quantify the spatial and temporal variability of exhumation within this orogen-scale feature.

The Gondasampa transect exposed ~ 40 km north-northwest of the summit of Cho Oyo contains garnet bearing schist and gneiss within a 150 m-thick mylonite zone. Assemblages preserved in these rocks record a peak temperature of ~730°C and a pressure of ~8 kbars. Previously published results from the north side of Mt. Everest (Rongbuk valley) yield P-T estimates of 630°C and 4.6 kbars. Additionally, new geothermobarometric data from the Kharta area (~60km NE of Everest) yield 680-720°C and 6-7 kbars for samples collected within the upper 2 km of the GHS.

There is also significant along-strike variability in the macro- and micro-scale structure of the STDS between these three transects. The Gondasampa and Rongbuk transects preserve a comparable sequence of lithologies in a 150-300 m thick mylonite zone that grades structurally down into migmatitic gneiss. Across this zone, deformation mechanisms evolve from a distributed shear zone of high-grade gneiss, through a narrowing mylonite zone into a discrete detachment. In contrast, the STDS at Kharta is manifested as a ~1000 m-thick zone of distributed shear that displaces high-grade gneisses, calc-mylonites and marbles beneath sedimentary rocks.

Variations in peak P-T within, and 100's of meters below, the mylonite zone are attributed to variable amounts of extrusion and exhumation along the STDS. We interpret the 1000 m-thick mylonite zone of the Kharta area as representing the earlier stages of exhumation along the STDS whereas the STDS as recorded in Rongbuk and Gondasampa preserve the later stages of exhumation that progressed into a narrow zone and brittle detachment. Additionally, we emphasize that exhumation of the GHS was accommodated by deformation that was partitioned into a relatively narrow shear zone (STDS) along the upper margin of the GHS.

## **Using inclusion trails to refine P-T-d paths in the Rodinian LP/HT terrane of the Mount Isa window, Australia**

Mohammad Sayab

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Rodinian Mesoproterozoic terranes exhibit complex tectonometamorphic histories generally considered to result from low-pressure/high-temperature (LPHT) metamorphism with an anticlockwise pressure (P) -temperature (T) path. Yet studies regarding the tectonic regime responsible for such P-T-t paths have been quite limited. Measurement of inclusion trails in porphyroblasts of the Mesoproterozoic Mount Isa Inlier, NE Australia, has allowed to define two orogenic cycles and associated phase of metamorphism that could not previously be distinguished from one another. A newly recognized early orogenic cycle involved N-S crustal shortening that produced W-E trending structures with associated metamorphism M1. This was followed by a second well-established orogenic cycle involving W-E bulk shortening that produced N-S oriented structures and associated metamorphism M2. Crustal thickening during M1 followed by near-isothermal decompression led to low-pressure/high-temperature (LP/HT) conditions. This was then followed by a second prograde path towards middle- to upper- amphibolite facies metamorphism M2. This polyorogenic history can be correlated with the tectono-metamorphic evolution of other Mesoproterozoic terranes in northern Australia and in the SW United States providing new constraints on the paleogeography of the Rodinia supercontinent.

## **Distribution, chronology and causes of Cenozoic exhumation in the southern British Isles**

Simon P. Holford<sup>1</sup>, Jonathan P. Turner\*<sup>1</sup>, Richard R. Hillis<sup>2</sup>, Paul F. Green<sup>3</sup>, Anthony G. Doré<sup>4</sup>, Robert W. Gatliff<sup>5</sup>, Martyn S. Stoker<sup>5</sup>, Kenneth Thomson<sup>1</sup>, John R. Underhill<sup>6</sup> and Gareth A. Williams<sup>7</sup>

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Presently outcropping rocks in the southern British Isles have been previously more deeply buried by up to 2.5 km of section that has been removed due to uplift and erosion during Cenozoic times. This profound exhumation controls the geological outcrop pattern, physiography and distribution of hydrocarbon resources in the southern British Isles. Exhumation has been explained in terms of either igneous underplating of the lower crust related to the Iceland mantle plume during the early Palaeogene, or shortening of the crust due to plate boundary forces, such as Alpine collision, transmitted into the plate interior. Plate-wide compression requires a high strength crust able to transmit stresses into the plate interior from plate boundary interactions ~1000 km distant. A detailed understanding of the distribution and chronology of Cenozoic exhumation is required to discriminate between these hypotheses.

Here we describe the distribution and chronology of Cenozoic exhumation in the southern British Isles based on a new compilation of apatite fission-track analysis (AFTA), vitrinite reflectance, sedimentary rock compaction and seismic reflection data. Our data demonstrate major short-wavelength variations in exhumation over Cenozoic compressional structures, and they show also that exhumation extends to areas beyond the postulated influence of underplating, such as the southern North Sea. Furthermore, our AFTA and compaction data indicate that in many areas, including the Irish Sea (considered by proponents of the hypothesis to be the focus of underplating), a large component of Cenozoic exhumation was of Neogene age, consistent with the age of contractional deformation in the study area and inconsistent with early Palaeogene underplating. Hence we argue that crustal shortening was the major cause of Cenozoic exhumation across the southern British Isles. Neither the distribution nor chronology of the exhumation support underplating as the principal mechanism that drove it.

## The unroofing of an orogen

Tim Dempster <sup>\*1</sup>, Liam Reinhardt<sup>2</sup>, Stewart Clark<sup>3</sup> and Cristina Persano<sup>1</sup>

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The denudation history of the rapidly uplifting Spanish Sierra Nevada has been unravelled using both apatite fission track (AFT) ages and <sup>10</sup>Be analyses of bedrock, fluvial sediments and Neogene conglomerates. Major contrasts in the denudation history are linked to the integration of tectonic and erosional processes. Upland areas are characterised by low-relief, low slope angles and the preservation of shallow marine sediments, which have experienced <200 m of erosion in the last 9 Ma. However, AFT determinations from samples close to the marine sediments imply >2 km of denudation since ~4 Ma. The minimum denudation rates of 0.4 mm.a<sup>-1</sup> derived from AFT also contrast with the medium-term (10<sup>4</sup> a) slow erosion rates (0.04 mm.a<sup>-1</sup>) estimated from <sup>10</sup>Be measurements at high elevations. The local contrasts in denudation rates within the high Sierra Nevada indicate that most of the unroofing occurs by tectonic denudation on flat-lying detachments. In lower elevation areas, rapid river incision coupled to rock uplift has produced ~1.5 km of relief implying that hillslopes close to the edge of the orogen are sensitive to normal-fault-driven changes in base-level. However, these changes are not transmitted into the low-relief slowly eroding upland areas. Thus, the core of the mountain range continues to increase in elevation until the limits of crustal strength are reached and tectonic denudation is initiated along planes of structural weakness. *We suggest that this form of denudation dominates the unroofing of the Sierra Nevada and may provide an effective limit to relief in such orogens.*

The first pulse of major erosional denudation at the margins of the mountain block produced thick proximal 5.5 - 7 Ma conglomerates in the adjacent Granada Basin. The influence of this type of unroofing has been studied using thermochronology on both individual clasts and the adjacent source rocks. This reveals that: 1. Major depositional pulses are represented by extremely local erosion and are not recorded as significant events by thermochronometers cooling in the basement. 2. Hydrothermal activity within sedimentary deposits may cause significant resetting of the detrital thermochronological signatures. 3. In such environments, conglomerate clasts record different thermochronological information to matrix grains.

The lack of a thermochronological signature in the basement that can be related to an apparently major erosional event is surprising and casts doubt on the ability to read erosional denudation of ancient orogens using thermochronology. A number of factors might account for this lack of correlation between events in the basin and the cooling history in the basement.

*The timing of erosional denudation is divorced from the time of basement cooling.*

*Erosion has a relatively minor influence on the cooling of the unroofing orogen.*

We conclude that many individual mountain blocks cool by tectonic denudation rather than erosion. Coupled to this the amount of crust that can be readily removed by erosion from catchments is small relative to the resolution with which thermochronometers are able to constrain cooling events. Hence the detrital record of denudation preserved in sediments may have little bearing on the overall denudation of orogens and thermochronology typically records tectonism not erosion.

## Arabia-Eurasia collision: multiple causes of Oligocene global climate cooling?

Mark Allen\*<sup>1</sup> and Howard Armstrong<sup>1</sup>

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The end of the Eocene greenhouse world was the most dramatic phase in the long-term cooling trend of the Cenozoic era. Onset of Antarctic glaciation preceded rapid global cooling at 34-33 Ma in the Oi-1 event. Here we show that the Arabia-Eurasia collision and the closure of the Tethys ocean gateway began in the Late Eocene at ~35 Ma, up to 20 million years earlier than commonly assumed in plate tectonic and oceanographic models. Four effects of the collision had the potential to cause global cooling. (1) Reduction in CO<sub>2</sub> output occurred, as arc volcanism waned abruptly across southwest Asia. During the Eocene volcanic successions up to ~8 km thick accumulated over an area of >10<sup>6</sup> km<sup>2</sup>. By the Oligocene volcanism had diminished to scattered centres. (2) Organic carbon storage in Paratethyan basins would have reduced atmospheric CO<sub>2</sub>. Total organic carbon stored in these basins is ~60 x 10<sup>12</sup> T, accumulated at a rate equivalent to ~12% of the estimated global organic carbon flux in the late Paleogene. (3) Collision increased surface exposure and silicate weathering, thereby reducing CO<sub>2</sub> levels by an unconstrained amount. (4) Plate convergence and initial collision reduced the flow of warm Tethyan waters into the Atlantic, thereby reducing poleward heat transport. All four mechanisms may have acted together to take the Earth across a threshold into the icehouse world.

## **Investigating the relationship between fault permeability, pore pressure and effective stress using constraints from reservoir induced seismicity.**

Rebecca J. Lunn<sup>1\*</sup>, Aderson F. do Nascimento<sup>2</sup>, Zoe K. Shipton<sup>3</sup>, Patience A. Cowie<sup>4</sup>

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Understanding the role of geological faults in fluid flow and chemical transport is critical for oil and gas, waste disposal and deep storage industries. Faults can traverse many lithological sequences, forming large-scale structures that span several kilometres laterally and over depth; their sheer physical extent implies that their hydraulic properties have a major influence on deep flow systems. This research uses observations of reservoir-induced seismicity (RIS) beneath Açú Reservoir, NE Brazil, to investigate the damage zone permeability of geological faults in crystalline basement rocks. High-resolution digital seismic monitoring of the reservoir has provided detailed information on the locations of seismic events. The temporal distribution of these events shows them to be directly related to annual fluctuations in the reservoir level. Model simulations, using a decoupled hydromechanical formulation (i.e. a static permeability field decreasing exponentially over depth due to increased confining pressure), show that pressure-diffusion is a hydrogeologically consistent mechanism for RIS, if preferential flow occurs within 2D fault planes embedded in a 3D low permeability matrix. Predictions of the maximum pressure change in these faults at hypocentral depths indicate <0.05 kPa is required to trigger seismic events. Further, the observed spatial and temporal variability of earthquakes indicate that these faults must have heterogeneous permeability fields with significant spatial structure; pockets of high and low permeability of the order of 0.5 - 1.5 km in diameter.

This research demonstrates for the first time that microseismicity data can be successfully employed to image spatial and temporal evolution of fault permeability. Further analyses of the Açú data are on-going to improve the accuracy of hypocentral locations and to investigate earthquake co-location and healing rates. A fully coupled hydro-mechanical model, MOPEDZ will be applied to simulate pressure-diffusion within the fault plane and hence to provide a more detailed understanding of the coupled evolution of seismicity and permeability.

## Predicting fracture and porosity evolution in Dolostone

Julia F.W. Gale <sup>\*1</sup>, Robert H. Lander <sup>2</sup> and Robert M. Reed <sup>1</sup>

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Fracture growth and diagenesis interact to create and destroy fracture porosity in dolostones and thereby affect fluid-flow properties in these important hydrocarbon reservoir rocks. We have observed dolomite crystals that bridge fracture walls in several dolostones. These bridges are similar to the quartz bridges that commonly occur in fractured sandstones. Quartz-bridge morphologies in fractured sandstones have been replicated using geometric crystal growth models that consider anisotropies in growth rates associated with crystallographic orientation, euhedral versus non-euhedral nucleation surfaces, and the influence of repeated episodes of crystal breakage during incremental fracture opening. Our analysis of detailed SEM-CL images from fractured dolostones suggests that similar linked mechanical and chemical processes could cause the formation of dolomite bridges.

To evaluate this hypothesis we developed a geometric crystal growth model for dolomite fracture fill in fractured dolostones and evaluated the ability of the model to replicate microstructures within dolomite fracture cement. We used an SEM-CL image of an Ordovician, Knox Group dolostone as a basis for the model host rock and then introduced periodic incremental fracture-opening events while simulating concurrent cement growth. We assumed equivalent growth rates along each euhedral growth face (as suggested by SEM-CL images, which show little growth anisotropy) and 20 times faster growth rates on non-euhedral versus euhedral surfaces on the basis of analogy with quartz (comparable data are lacking for dolomite). Several model runs were completed with different fracture-opening rates. The results were compared with natural fracture morphologies, producing the anticipated replication of bridges and lining cement morphologies, but also yielding some unanticipated but logical results. In particular, we found that modelled dolomite bridges commonly have rhombic shapes even when they are subjected to multiple crystal breakage episodes. In addition, the crystal growth model predicts morphologies that are analogous to features in SEM-CL images that superficially appear to be caused by crystal dissolution.

## Footwall extension during low-angle normal faulting: controls on fault zone structure and fluid flow

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Many previous studies have documented pervasive *hangingwall* deformation associated with low-angle normal faults (LANF) and metamorphic core complexes, indicating significant horizontal extension above the evolving fault zone. However, on the Island of Elba, Italy, extension in the immediate *footwall* of the Zuccale LANF reaches 60%, involves a complex kinematic history, and locally exerts a strong influence on fault zone thickness and the internal distribution of fault rocks. The Zuccale LANF was active between *c.*13-4 Ma at a dip of 15° east, and slipped under a regional stress field characterized by vertical  $\sigma_1$ . Stratigraphic offsets suggest a displacement of 6-8km. Early extensional structures in the footwall formed as sub-horizontal or LANF-parallel semi-brittle cataclastic shears. These are crosscut by higher-angle brittle normal faults which often show listric (in 2D) or 'spoon-shaped' (in 3D) geometries and can be broadly subdivided in to an older and younger set. The older faults currently dip on average 35° east and accommodated E-directed extension. They are crosscut and rotated by the youngest set of footwall faults which dip on average 60° east, but accommodated SSE-directed extension, possibly as a consequence of intrusion of the *c.*5.9 Ma Porto Azzurro pluton at shallow depths beneath the fault zone. Where the core of the Zuccale LANF is well exposed, high-angle footwall structures are observed to link directly into the base of the fault zone causing the fault core to increase in thickness from ~3 to ~8 metres. Synchronous movement along the main LANF and high-angle footwall structures is recorded by east-verging asymmetric folding of the fault rock foliation directly above footwall faults. Two observations indicate that these footwall faults have an important role to play throughout the history of the main LANF; 1. Early-formed fault rocks such as chlorite- and talc-rich phyllites have been isolated and 'protected' from subsequent detachment faulting where they lie in the hangingwall ('lee') of high-angle faults that thicken the fault core. This indicates that footwall structures must have been active relatively early and has important consequences for transmitting weakening mechanisms and for the permeability structure of the fault zone. 2. Hydrofracture veins which link downwards in to footwall faults crosscut the main fault zone, suggesting periodic release of trapped footwall fluids. Locally, channelling of fluids by footwall faults allowed build ups in fluid overpressure beneath the low-permeability fault core which resulted in large scale fluidization of pre-existing quartzite cataclasite. The fluidized cataclasite, which is exposed over an area ~50x30 metres, contains at least three internal variations, defined by colour, matrix texture and average clast size. All three variations 'intrude' the base of the fault zone, disrupt the overlying fault rock sequence, and are cut at different levels by discrete brittle detachment surfaces, indicating multiple episodes of fluid overpressure development. Our observations suggest that deformation and fluid circulation in the footwalls of LANF are more important than previously recognised, and may provide essential insights into the mechanics of LANF and the generation of seismicity in such regions.



## **On the origin and distribution of fracture damage surrounding strike-slip fault zones: implications for fluid flow**

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Fault damage zones are represented by both microfracturing of the rock matrix and by macroscopic fracture networks. The spatial distribution and geometric characterization of fracture patterns at various scales help to predict fault growth processes, subsequent mechanics and bulk hydraulic properties of a fault zone. We studied strike-slip faults of various displacements that cut crystalline rock (granodiorite) within the excellently exposed and passively exhumed Atacama Fault Zone, Northern Chile. Micro- and macroscale fracture densities within the damage zones of faults with well-constrained displacements ranging over 3 orders of magnitude ( $\sim 0.12$  m – 5000 m) have been characterized. These faults can be compared and contrasted as they all cut the same rock type.

Multiple generations of microfractures indicating deformation at different crustal depths and times are represented by fluid inclusion planes (FIPs), partially healed, and open microfractures. The FIPs show a log-linear decrease in density with perpendicular distance from the fault plane on all faults studied. These FIPs are in a predominantly mode I orientation and we interpret them to record a snapshot of fault history related to the passage of a migrating fault tip process zone. All faults appear to have a critical microfracture density independent of displacement. However, fault damage zone widths scale with displacement. Later microfractures do not show a clear relationship of microfracture density with distance. We believe we have successfully isolated fracture damage which is related to fault tip processes, and the damage zone width scales linearly with the active fault length (proportional to fault displacement), which is consistent with a post-yield fracture mechanics model. Macrofractures are a combination of shear and opening mode, but a significant proportion also occur at a high angle to the main fault trace, which may be related to dynamic loading or hydrofracturing with the greatest principal stress oriented at a high angle to the fault trace.

It has been thought that the overall fault structure of large displacement zones is established early in a fault's history. We interpret the microfracture damage surrounding the faults studied accumulated as a result of the initial process zone migration; geometrical irregularities on the fault plane and dynamic loading have also contributed to off-fault damage, although this is less well understood. Early fault damage zone width scales with displacement, and core structure becomes more complex with increased displacement. By separating damage from fault tip processes from dynamic slip induced damage, we can make better estimates of fracture energies related to slip events, and also better understand how fault zone permeability evolves with time. Using a triaxial deformation apparatus we have measured experimentally the pre-yield permeability and porosity evolution with progressive brittle deformation of initially intact quartzofeldspathic crystalline samples as a proxy for varying degrees of fracturing found within fault damage zones, and characterized the development of permeability anisotropy with progressive deformation. To understand the fundamental fault growth processes and their effect on fluid transport around large strike-slip fault zones, this fault damage generated in laboratory samples have been quantified and related back to microscale damage observed in the field, providing a quantitative tool for predicting natural fluid flow properties.

## **On the formation of and fluid pressure within strike-slip dilatational jogs: constraints on crustal stresses at depth**

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Dilatational jogs on strike-slip faults provide a pathway for enhanced fluid flow and are typically sites for hydrothermal mineral deposition. We describe an excellently preserved strike-slip extensional duplex from the Atacama fault system, northern Chile. The depth of formation of this duplex is constrained to at least 3 km depth. Quartz and calcite veins from the duplex contain fluid inclusions that indicate that during duplex formation boiling occurred, resulting in mineral deposition at temperatures up to 252°C and at pressures between 0.4 and 7 MPa. Vein microstructures indicate mineral growth into open space and hence the least principal stress ( $\sigma_3$ ) is constrained to a maximum value of 7 MPa presumably as a result of the overlapping fault geometry. The maximum principal stress ( $\sigma_1$ ) in a strike-slip regime must be greater than the overburden pressure (~81 MPa) and hence minimum ( $\sigma_1 - \sigma_3$ )  $\approx 4T$  where  $T$  is the measured tensile strength of the rock, predicting extensional or hybrid extensional shear fracturing, consistent with field observations. The low value for  $\sigma_3$  at failure suggests that failure might have been promoted as much by reduction of  $\sigma_3$  as an increase in  $\sigma_1$  (load strengthening) as is typically assumed for strike-slip faulting. The sub-hydrostatic fluid pressures indicate that the dilatational jog was hydraulically isolated during formation and show that fluid pressure was not the driving force for failure. The data presented provide quantitative constraints on the state of stress at depth within these important tectonic structures.

## How strong is the Alpine fault? Evidence from fluid flow and deformation partitioning in the Pacific plate hanging-wall, New Zealand

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An array of near-vertical backshears in the central Southern Alps, New Zealand, are interpreted to have formed sequentially in an escalator-like fashion and to play an important role in channelling the upward flow of metamorphic fluids through this active orogen. The 1-2 km-wide array of backshears is exposed only in the central region of the Southern Alps around Fox and Franz Josef glaciers. There, fluid inclusion, stable isotope, and thermochronometric data indicate shear failure of a transiently embrittled lower crust down to depths of >20 km. In quartzofeldspathic schist, the shears initiated and accumulated slip brittily (but probably steadily and aseismically) but ductilely in weaker, pre-existing quartz veins that were subject to finite shear strains averaging  $4.8 \pm 0.8$ . Blunting of the brittle crack-tips into the coherently deformed quartz veins suggests that ductile flow was the rate-controlling factor during backshear deformation. The backshears are systematically spaced ( $53 \pm 4.7$  cm), with an average slip of  $14.1 \pm 1.2$  cm in a direction pitching  $36^\circ$ SW and are dextral-oblique. Relative to plate motion, they accommodated an excess of margin-parallel dextral-slip. This situation implies some partitioning of oblique motion components between the Alpine Fault and its dextrally wrenched hanging-wall to the east. A corollary to this is that the Alpine Fault, despite its inferred thermally induced weakness, was not weak enough to accommodate perfectly plate motion-parallel slip at the time when the shears were active.

We infer that presence of fluid in the Pacific Plate crust was integral to the formation and accumulation of shear along these structures. Near-lithostatic fluid pressures were a chief agent that originally triggered deep embrittlement and shear failure at the lower crustal depths. After formation, hydrolytic weakening due to high water fugacity allowed deformation in the fluid-weakened quartz veins to accrue at high strain-rates but without sufficiently high differential stresses to cause their brittle failure. As the strength of these veins controlled that of the backshears terminating into them, this process may have significantly weakened the bulk strength of the Pacific Plate crust above the Alpine Fault ramp. The shears also provided a means for suprahydrostatic metamorphic fluids to escape upwards, acting as a closely spaced array of planar, vertical conduits cutting across the otherwise low permeability ( $1 \times 10^{-18}$  m<sup>2</sup>) schist. Upward draining of this metamorphic fluid into the hanging-wall would have left the underlying source region near its base residually drier. Fluid expulsion may thus have accomplished a net devolatilisation and rheological strengthening along the Alpine mylonite zone at depth at the same time that hydrolytic weakening softened structurally higher rocks in the hanging-wall. These fluid-related strength changes may have limited the degree to which the Alpine Fault could slip in the plate motion direction without some partitioning of deformation into its hanging-wall.

## **Normal growth fault evolution in the Columbus Basin, Trinidad**

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Normal growth faults record their displacement history in the stratigraphy of their wall rocks and hence yield essential information about fault evolution, including slip-rates, propagation history, and information on the linkage and displacement transfer on different fault segments. A series of normal growth faults in the Columbus Basin, offshore Trinidad, was investigated using a high-resolution commercial 3D seismic dataset. This, together with the rapid sedimentation rates, good well control and dating of key horizons, allows us to investigate the distribution and evolution of displacement, and address the fault growth mechanism.

The fault geometry, throw distribution and timing on two fault systems are presented: 1) a non-breached to breached relay fault interaction, 2) a fault showing en echelon splaying towards shallow levels from a continuous fault at depth. The displacement shows abrupt changes on different segments and for different horizons. Fault displacement back-stripping has been used to determine the amount of throw accumulated in various parts of these fault systems during several dated time intervals between 2.5 Ma and the present. Corrections for compaction have been applied to determine the initial throws and fault slip rates.

The evolution of fault slip rates is used to test models of fault growth and is therefore essential in exploration for oil and gas. Knowing the timing of fault activity in detail helps to constrain hydrocarbon trap formation, migration through active relay ramps and possible leakage or migration along faults.

## **Growth of normal faults during rift-raft tectonics; evidence from 3D seismic and well data, South Viking Graben, Quad 15/3**

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Rift-raft tectonics is used to describe the formation of normal faults in response to gravity-induced gliding and extension of brittle stratigraphic units above a mobile salt layer. The majority of previous studies have utilised only 2D seismic data and have only described the geometries and scales of rift-raft related structures. Furthermore, lack of well data or failure to integrate stratigraphic patterns with structural observations means that the temporal evolution of structures remains uncertain. In this study a 750 km<sup>2</sup> 3D seismic survey is coupled with well data to investigate the temporal and spatial evolution of a rift-raft related normal fault array on the hangingwall dipslope of the South Viking Graben, Northern North Sea. The South Viking Graben dips moderately (5-7°) to the west and is bound on its western margin by a N-S-trending, E-dipping, normal fault with >2 km of displacement. On the hangingwall dipslope of the half-graben, 10 km eastwards of the basin-bounding fault, three NE-SW-trending, moderate displacement (300-500 m) normal faults are observed, two of which are antithetic (i.e. west-dipping) and one of which is synthetic (i.e. east-dipping) to the basin-bounding fault zone. The faults have markedly different geometries at depth; the central fault has a distinct listric geometry whereas the westernmost and easternmost faults are planar. All the faults appear to terminate downwards into an evaporite-bearing sequence of Permian age. Within the hangingwall of the listric fault a rollover anticline is developed, the crest of which is intensely deformed by NE-SW-trending, low-displacement normal faults. It is interpreted that these faults formed in response to westwards tilting of the hangingwall during activity on the basin-bounding fault down-dip to the west and consequent westward gliding of the post-Permian stratigraphy over the underlying evaporite-bearing sequence. Isochron mapping of the 3 sub-units within the syn-rift succession allows temporal constraints to be placed on the evolution of the hangingwall dipslope normal faults and indicates marked diachroneity in the initiation and subsequent cessation of fault activity. Four key stages of structural development are observed; (1) initiation of activity along the central part of the easternmost fault, (2) lengthening of the easternmost fault by lateral tip propagation and initiation of activity along the northern segment of the central fault, (3) southwards propagation of the central fault and initiation of activity on the easternmost fault, and (4) cessation of activity on all faults. The progressive upslope migration of fault activity observed here reflects progressive “unbuttressing” of updip, post-salt cover stratigraphy, and shares many characteristics with “raft tectonics” described from other mobile salt/shale-influenced settings (e.g. offshore Brazil, West Africa, Borneo). Interestingly, this fault array evolution differs from that observed in rift basins lacking mobile layers at-depth where deformation is typically localised onto a few large displacement structures through time and such a predictable (i.e. upslope) migration of fault activity is not observed. This study highlights the importance of at-depth mobile layers on fault kinematics during basin extension and demonstrates that an improved understanding of fault growth can be obtained through the integration of 3D seismic and well data.

## Controls and timing of structural inversion in the NE Atlantic Margin

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Continental margins were once thought to be 'passive' in nature. However, the NE Atlantic margin shows evidence for inversion during the Cenozoic. The interpretation of newly acquired and existing 2-D seismic data from the Faroe Shelf to the Rockall Plateau has revealed Cenozoic folds along the NE Atlantic Margin (eg. Hatton Bank, Ymir and Wyville Thomson Ridges). Certain features such as, the Lousy, Bill Bailey's and Faroe Banks, have long been ascribed to non-compressional events. New seismic data, however, suggests that these features are indeed the result of compression.

Unconformities that have been mapped and dated along the NE Atlantic Margin show that the growth of compressional features occurred during distinct periods in the Cenozoic - the late Ypresian, late Lutetian, Late Eocene, Early Oligocene, Mid Oligocene, Late Oligocene, Miocene and Early Pliocene. Some compressional phases, such as the Late Eocene, appear to traverse the entire margin while others are more localised.

It remains unclear what the main driver of the deformation was. However, horizontal compression within the NE Atlantic Margin resulting from ridge push, Alpine stresses, depth-dependent stretching and/or plate reorganisation may all have played a role at one time or another. If they are not dependent upon the disposition of pre-existing structures, sediment loading or lithospheric structure, the temporal and spatial variation in the orientation, location, nature and timing of compressional features may be indicative of the inversion mechanisms involved.

## **Structural style of the Malargüe fold-and-thrust belt at the Rio Diamante area, Mendoza province, Argentina.**

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The Malargüe fold-and-thrust belt is a thick-skinned one developed in Miocene-Pliocene times during the Andean orogeny, in Mendoza province, Argentina. It is well known that the tectonics of this mountain chain involves both basement and cover rocks. The former are mainly plutonic and volcanic rocks formed during the Gondwanic magmatic cycle (Carboniferous-Triassic). These rocks formed the basement of Mesozoic marine and nonmarine sediments in the Neuquén basin. Large amounts of Cenozoic sintectonic materials fill the foreland basins related to the Andean orogeny. In order to understand the structural behaviour of all these rocks we made a detailed mapping (1:50.000) in the Rio Diamante area, approximately located between 34° 30' and 34° 45' south latitude and 69°30' and 69° 50' west longitude. In this sector of almost 1200 km<sup>2</sup> (35 km x 34 km) we constructed three regional cross-sections that allowed us to recognize the geometry of the structures and so to propose a probable structural evolution of this Andean region. From a regional point of view, the main structures are two uplifted basement blocks that occur at both the west and east sectors of the study area surrounding a central region where thin-skinned deformation prevails. Although the basement rocks at the western block are not apparent, its uplift is evidenced by the occurrence of Jurassic marine rocks at very high topographic levels. The eastern block that belongs to the Cordillera Frontal morphostructural unit is a huge range of basement rocks overthrust to the east and its south edge is located in the Rio Diamante's valley. An interesting feature is the common development of backthrust systems at the toes of these basement blocks. Everywhere basement rocks appear at the surface it is possible to observe these backthrusts related with them. The folds formed by these west-directed thrusts have a particular geometry including slightly tilted, long backlimbs, steeply-dipping, short forelimbs and widely spaced backthrusts, which cannot be explained with certainty by classical models. Geometric and kinematic studies, supported by seismic and well information, allow interpreting a structural style characterized by large basement wedges, that may be related to low or medium angle thrust faults. These wedges propagate into the sedimentary cover along favourable horizons (commonly gypsum), transferring the shortening from the basement to the cover suggesting a close spatial and temporal relationship between basement and cover deformation. Some workers suggest that tectonic inversion was important in this region. However we think that this mechanism doesn't explain the amount of shortening observed in this area and thus it can't be considered likely in the orogenic building of this part of the Andes. In the thin-skinned zone there is a distinct behaviour according to the variations of thickness and composition of the rocks, related to changes in the environment from a deeper to shallow portion of the basin. While at the western zone the abundance of shales and salt horizons facilitate the formation of tight folding, generally interpreted as fault-propagation folds, the more competent units placed at the eastern zone, mainly composed by calcareous strata, are deformed into duplex structures and imbricated fans. Toward the south, these thrust systems overthrust Cretaceous rocks upon Miocene synorogenic units.

## Variation in deformation style within a fold-thrust belt

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Using satellite images and remote mapping, the Zagros Simply Folded Belt is ideal for the study of progressive deformation at a convergent margin. In the Simply Folded Belt, lines of anomalously long, high-aspect ratio folds are marked by lines of wind gaps and major river diversions. These are evidently major structures clearly linked to movement along major basement thrusts and correlating with major steps in the landscape. These formed sequentially as the deformation front progressed towards the Persian Gulf. Important pulses of movement on these faults generated the long overlying folds and lead to the abandonment of river channels and the formation of wind gaps.

In the Zagros Belt brittle and ductile deformation processes interact. Movement along a ramping-up thrust creates a fault-bend fold. Compressive stresses build up, leading to serial folding in the cover behind the fault-bend fold. Eventually, deformation of the block requires stresses in excess of those required to form a new thrust. The original thrust is abandoned, the footwall collapses and the process repeats. This model also provides an explanation for periodicity in shortening reported in earlier work (Sattarzadeh\*, 1997).

Current mapping in the Sawtooth Range, Montana, indicates that the situation is more complicated than this. A detailed study of a fold pair in the frontal region of a fold-thrust belt indicates that folds may change character along their length. The Teton anticline and Little Teton Anticline are both incipient box folds with broad rounded hinges formed in the carbonates of the Madison Group. The fold wavelength varies as a function of the depth of the detachment, which ramps up from the Cambrian shales in the hinterland, to Devonian shales and finally Cretaceous shales in the foreland. Both anticlines strike N-S, with the dip of the forelimb becoming steeper along strike. The Teton Anticline is a near symmetrical fold in the northern mapped section but becomes distinctly asymmetric several km to the south. On the leading edge of this fold pair, small-scale buckle folds are seen in the Kootenai formation. These folds have narrow rounded hinges and small wavelengths.

The change in character of the Teton Anticline implies that at some point along strike, a thrust fault develops in the core of the fold, although in the north of the region, the fold is clearly a detachment fold with incipient fixed hinges. Little Teton Anticline also shows some asymmetry before plunging out in the south of the mapped area. These observations indicate that folding in a fold-thrust belt can display a spectrum of different geometries ranging between the end-member detachment fold and the fault-related fold and that these differences, which are determined by the relative amounts of brittle and ductile deformation, can occur along strike of the same fold.

(\*Sattarzadeh, unpublished PhD thesis, University of London)



## **Fracture zone orientations onshore Faroe Islands (North Atlantic); Evidence for dual rifting episodes?**

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The Faroe Islands are located in the North Atlantic, between Scotland and Iceland. The pre-Quaternary geology consists predominantly of subaerial basalt lava flows, which were extruded in the Palaeocene to Eocene and forms part of the North Atlantic Igneous Province. The oldest rocks crop out towards the South and Northwest, while the youngest rocks are exposed in the central and North-eastern part of the islands.

Little has been done in order to investigate the tectonic history of the islands, possibly due to the relatively flat lying succession of basalt flows, with layers dipping less than 4° on most of the islands. The only exceptions are on the southernmost island (Suðuroy), where it is up to 6°, and on the westernmost island (Mykines), where it is up to 18°. The direction of the dip varies slightly across the islands, with a broad E-W trending syncline being located in the central part of the islands, and an E-W trending anticline being located on the northern islands. Recent work has suggested a correlation between the measured dips and pre-existing basement highs.

The primary data used in this project are colour aerial photos obtained since 2002 and the only area currently not is the central island of Sandoy.

There is a difference between the fracture orientation in the south and partly west compared to the northeast. The south shows a unimodal NNW-SSE trend. The northern islands all show a bimodal E-W to ENE-WSW trends. The north-western part of the islands also appear to show an additional NW-SE trend, which may be related to the NNW-SSE trend found on Suðuroy. On Suðuroy, faults within the oldest volcanic series are observed dying out and not penetrating the younger overlying strata, indicating that there is a temporal relationship between the fracture orientations in the south compared to the north of the island.

Work suggests that the NNW-SSE fracture orientations are linked to a suggested transient rifting event in the Early Palaeocene. This rifting event is expected to have been located to the west of the islands, and the extrusion of the oldest volcanic rocks is thought to be associated with this rifting event.

The E-W to ENE-WSW fracture orientations can be temporally linked to have occurred during the emplacement of the youngest lava formation, which is extruded during the final continental breakup in the Early Eocene.

Current theory suggests that Munkagrunnur Ridge, where Suðuroy is located, was created by compressive forces in the Oligocene and Miocene. Our findings suggest that the older fault trend is associated with a proposed transient rifting event west of the Faroe Islands in the Early Palaeocene, while the younger fault trends can be linked to the final continental breakup in the Early Eocene.

## **Recent tectonics of Outer Carpathians based on fractured clasts (first results)**

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### **Fractured clasts in the Outer Carpathians**

Paraconglomerates within the Polish segment of the Outer Carpathians. In the studied localities, architecture of fractures is well-organized and independent of clasts' textural properties. It appears, therefore, that the fractures are tectonic features. Gravels and paraconglomerates bearing fractured clasts are exposed mainly close to the map-scale thrusts, strike-slip faults and normal faults. This points to the ongoing tectonic activity of the map-scale structures.

### **Fractured clasts and Recent tectonics of the Outer Carpathians**

The main tectonic features of the Outer Carpathians were formed during Eocene through Miocene subduction, subsequent Miocene collision, and Miocene to Recent collapse. The kinematics of the ongoing faulting has not been reconstructed yet; hence, the reason for the faulting is poorly understood. The most plausible explanations are: (1) ongoing post-collisional shortening, (2) ongoing collapse, or both (1, 2).

### **Fractured clasts and earthquake risk in the Outer Carpathians**

Fractured clasts have been observed in numerous areas of recent, and historical seismicity. Consequently, the origin of fracturing is believed to be related to earthquakes. Fractured clasts occur commonly in Miocene conglomerates within the Vietnamese segment of the Red River Fault Zone. However, in the latter area Holocene gravels are devoid of fractured clasts. The area is recently seismically active, with historical earthquakes attaining magnitudes up to 5.5. We believe, therefore, that clast fracturing takes place only if magnitude of the related earthquake exceeds 5.5.

The Polish segment of the Outer Carpathians is considered to have been largely aseismic during recent times. Therefore, the seismic risk in the region is considered to be negligible or not-existing. However, the period of historical record in the region is rather short. It appears that geological record of numerous strong (>5.5) earthquakes in the region should compel us to reconsider seismic risk in this area.

## **Fracture patterns in thrust-related anticlines: case histories from the Apennines, Pyrenees and Zagros thrust-fold belts**

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Folding related fractures exert a first-order role on the migration and accumulation of fluids in reservoirs within thrust wedges, particularly when carbonatic multilayers are involved in the folding process. The type, frequency and attitude of these structures are controlled by several factors, including the kinematic mechanism of folding, the structural position within the fold, the mechanical stratigraphy and the environmental conditions of deformation. All these dependences imply a strong variability of fracture features within reservoir-scale anticlines.

In this contribution we illustrate the workflow that we set up for fracture data collection and analysis. We also illustrate fracture datasets collected in thrust related anticlines from the Apennines, Pyrenees and Zagros thrust-fold belts. We statistically analyse the variability of fracture attributes and quantify their relationships with the host fold geometry. Our results may provide guidelines for fracture pattern predictions in thrust-related reservoirs, thus contributing to improve their modelling.

## **The kinematic history of the Khlong Marui and Ranong Faults, Southern Thailand.**

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The NE-SW trending Khlong Marui Fault (KMF) and Ranong Fault (RF) are usually shown on maps as simple linear features, and are assumed to be conjugate to the NW-SE trending Three Pagodas and Mae Ping faults in northern Thailand. These northern structures belong to a population of large strike-slip faults which include the Ailao Shan – Red River Fault of South China and Vietnam. They radiate away from the eastern Himalayan syntaxis, and divide mainland Southeast Asia into several blocks. A diachronous reversal in displacement sense on the NW trending faults has been correlated to northward movement of the Indian indenter. It is therefore expected that the KMF and RF will have experienced a slip sense reversal opposite to, but at the same time as, the Three Pagodas fault.

Deformation on the KMF is focused on a zone of faults which is over 20 km wide, extends up to 200 km across Peninsular Thailand, offshore into the Andaman sea, and may either die out, or pass into the Gulf of Thailand at its northern end. The faults have clear topographic expression, especially in the region around Phang Nga. Extensive fieldwork has revealed a narrow sliver of mylonitised sediments and granitic intrusions which show that the fault has experienced significant dextral strike-slip motion under ductile conditions during its early history. A prolonged period of inversion occurred as the ductile core passed upwards through the ductile – brittle transition, culminating in sinistral slip along brittle faults which formed broadly parallel to the mylonitic foliation. Uplift continued after the cessation of strike-slip movement, bringing the ductile fault core to the surface along dip-slip faults.

The observed kinematics of the KMF are in accordance with its hypothesised role as an antithetic branch of the structurally similar Three Pagodas and Mae Ping Faults. The key remaining question to confirm this relationship regards the timing of movement. Samples from the fault core will be used for  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  geochronological analysis. Combining these data with the field results presented here, and similar future studies on the Ranong fault will help to constrain the role of strike-slip faulting in Himalayan extrusion tectonics, and the evolution of Southeast Asia.

## **How to constrain the fault activity history of individual faults on timescales of thousands to millions of years.**

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The spatial and temporal accumulation of slip from multiple earthquake cycles on active faults is poorly understood. Here, we describe a methodology that can determine the time period of observation necessary to reliably constrain fault behaviour, using marine high-resolution reflection seismology and a constrained stratigraphy. Detailed studies of active faults in New Zealand and Greece show that while displacement profiles are consistent for longer time periods, profiles determined for short time intervals (2 - 3 kyr) are highly irregular, with pronounced minima. This indicates temporal and spatial variability in incremental displacement associated with surface-rupturing slip events. There is spatial variability in slip rates along fault segments, with minima at locations of fault interaction or where fault linkage has occurred in the past. This evidence suggests that some earthquakes appear to have been confined to specific segments, whereas larger composite ruptures have involved the entire fault. The short-term variability in fault behaviour suggests that fault activity rates inferred from geodetic surveys or surface ruptures from a single earthquake, may not adequately represent the longer-term activity nor reflect its future behaviour. Different magnitude events may occur along the same fault segment, with asperities preventing whole segment rupture for smaller magnitude events.

## Plate boundary localisation in $<10^5$ years from $^{234}\text{U}$ - $^{230}\text{Th}$ dates from the 1981 Earthquake Fault, Greece

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In order to assess the timescale over which continental deformation can localise onto a single set of faults separating rigid plates we constrain the slip-rate history of an active normal fault using  $^{234}\text{U}$ - $^{230}\text{Th}$  coral dates from uplifted palaeoshorelines. We have studied Quaternary and Holocene palaeoshorelines and palaeoshoreface deposits exposed  $<2$ - $3$  km into the footwall of the 1981 Gulf of Corinth earthquake fault, Greece. We have dated in situ *Cladocora caespitosa* colonies collected adjacent to palaeoshoreline indicators and from shoreface sections. The ages and elevations of palaeoshorelines imply that uplift rates decrease along strike towards the lateral tip of the fault, and have increased through time. Between 250-150 ka, uplift-rates, and hence slip-rates increased by a factor of c. 3 at a time when other faults in the Gulf of Corinth ceased moving (382-112 ka). Presently-active and inactive faults slipped simultaneously prior to this time. The response time for the mechanism responsible for localisation of displacement onto a single line of fault is c.  $10^5$  years.

## Mechanical and structural control on aftershock rupture planes

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Moderate to large mainshock-fault-ruptures nucleating in extensional and compressional intracontinental environments are well explained by 2D frictional fault reactivation theory. Here we use a 3D slip tendency analysis to test whether aftershock sequences are also governed by fault reactivation theory. We observe that aftershocks for two well-documented seismic sequences occurring in extensional and compressional environments, the 1997  $M_w=6.0$  Colfiorito sequence (Central Italy) and the 1999  $M_w=7.5$  Chi-Chi sequence (Taiwan), respectively, nucleate on planes favourably oriented for frictional fault reactivation within the regional stress field. In particular, 89% of 329 and 81% of 121 events for the Colfiorito and Chi-Chi sequences respectively, are well explained by 3D fault reactivation theory. In the field of well explained ruptures the majority of the aftershocks nucleate on well oriented faults with geometry and kinematics consistent with the geological structures and only a small percentage of events occur on optimally oriented planes, 30% for Colfiorito and 15% for Chi-Chi. The nucleation of the aftershock ruptures as reactivation of the geological structures that represent well-oriented planes for fault reactivation in the regional stress field, suggests that aftershock ruptures are mainly controlled by pre-existing structures loaded to failure by tectonic stresses.

In addition, the percentage of well oriented aftershock rupture planes reaches 100% and 86% if we consider a  $M_w = 4.0$  threshold. We interpret this as the fact that stress rotations induced by the mainshock are unlikely or if present they are extremely localised and can influence only small structures capable of generating small magnitude aftershocks.

## **Evaporite bearing faults as a tool to understand the deformation processes into the seismogenic zone of the Northern Apennines (Italy)**

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In the Northern Apennines the integration of commercial seismic reflection profiles with the location of the mainshocks of the recent seismic sequences (the 1997 Mw = 6.0 Colfiorito and the 1998 Mw = 5.1 Gualdo Tadino) constrains the nucleation of the major events at ~6 km of depth within the Triassic Evaporites, TE, formation. In order to investigate the deformation processes responsible for earthquake nucleation we have studied ancient and exhumed Evaporites bearing faults cropping out in Tuscany.

Within the TE formation, that is a 2.5 km thick sequence, composed of decimetric-to-decameter scale interbeds of foliated gypsum-anhydrites and brecciated dolostones, we have studied fault zone architecture and deformation processes of both small (<10 m) and large (>100 m) displacement faults.

Small displacement faults shows a sharp reduction in grain-size when moving toward the boundary fault. Extreme localization of slip to discrete sliding surfaces (Y and B shear) is observed within the fine-grained cataclasite that at the same time is highly mineralised (Ca enrichment within the fine grained matrix). Large displacement faults, with up to 2 m thick fault core, are characterised by grey fault gouge, dolostone-rich fault breccia and cataclasites that in some cases evolve into foliated cataclasites with S-C fabric. Striated, discrete and straight slip surfaces are preserved within the foliated fault gouge. Field-based and microstructural studies document significant mineralization and fluid rock interaction during fault activity.

We propose that, during the interseismic phase, the transposed foliation (inherited fabric) and the thick layers of fault gouge enhanced the low permeability character of TE and favoured the build-up in fluid overpressures that promoted slip processes. Coseismic fluid release is associated to hydrofracturing within the brittle dolostones and mineralization within the dilatant fault core. Field data and inferred fluid assisted processes are in agreement with large scale evidences of sub-lithostatic fluid pressure encountered at depth in deep boreholes within the TE and positive correlation between fluid diffusion from a high pressure source located within the TE and time-space evolution of the 1997 Colfiorito aftershock sequence.



## Source mechanisms of acoustic emissions in triaxially loaded granite

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The process of brittle deformation and failure of rock is highly relevant to many aspects of Geoscience, such as seismology, tectonics and hydrofracture in hydrocarbons reservoirs. One possible approach in the study of this process is the application of damage mechanics, where time-dependent failure models involve the estimation of average internal damage as it varies with time. The growth of microcracks within a deforming rock can produce high frequency acoustic emissions (AE), which are suitable as an indicator of damage during laboratory experiments, but current models consistently overestimate the peak stress required to fail a rock sample. This project is concerned with the role of damage localisation in this overestimation and will employ AE laboratory data and microstructural analysis, in combination with mechanical observations, with the eventual aim of incorporating such effects into a predictive model of rock failure.

Current analysis of AE data involves investigating the microscale source mechanisms producing acoustic emissions. A source's 'moment tensor', a three by three matrix representing the mechanism acting at the source of an emission, can be found by inverting from P-wave amplitudes recorded at an array of sensors. Moment tensor inversion has been carried out for over 16,000 AEs recorded during the compressive loading of a cylindrical sample of red Aue granite. The resulting tensor elements were then decomposed, allowing events to be classified into predominantly shear, tensile and mixed-mode sources. The results are encouragingly similar to those of a polarity study carried out with the same data set. A clear shift in the dominant mechanism of cracking is visible between tensile sources, in the early stages of loading, and shear sources, during the later stages.

## **The structure of an exhumed seismogenic fault, Sierra Nevada, California**

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The physical properties, structural architecture and composition of fault zones at seismogenic depths play a key role in influencing the nucleation and propagation of earthquakes. For instance, many of the processes that could explain the dynamic reduction of shear resistance during earthquakes require that the zone that slips during a rupture event has a specific thickness. Geophysical studies can provide information on fault zone thickness, but provide a coarse view of spatial structure. Field studies of faults exhumed from seismogenic depths are therefore useful for constraining fault zone properties at depth. However, fault zone architecture is variable between different field areas and is likely to be dependent on pressure, temperature, strain rate and the presence or absence of fluids during deformation. In this study we present observations from a suite of faults that cut granitic rocks in Sequoia and Kings Canyon national park which share a similar architecture. K-Ar and apatite (U-Th)/He dating allow us to constrain temperature and pressure conditions during deformation. Ambient temperatures ranged from  $\geq 350^{\circ}\text{C}$  to  $< 100^{\circ}\text{C}$  as the host pluton cooled. The lithostatic pressure during pluton crystallisation has been estimated as 200 to 400 MPa. During the period of fault activity the lithostatic pressure decreased to  $\geq 100$  MPa in response to exhumation.

Detailed mapping has allowed us to develop a generic model of fault zone architecture for faults active under these specific pressure and temperature conditions. Faults in the study area are up to 10km long with displacements as great as  $\sim 100\text{m}$ . The fault zones contain one or more fault core strands centimetres to several metres in thickness. Fault cores are composed of one or more deformation elements, including cataclasites, ultracataclasites and pseudotachylytes. These brittle deformation elements overprint early ductile deformation. Principal slip zones are often defined by pseudotachylytes that are up to several centimetres in thickness. Cross-cutting pseudotachylyte veins suggest that deformation included multiple earthquake slip events. The co-seismic slipping zone delineated by pseudotachylyte generation surfaces has complex geometries. Secondary fractures are present both between and outside of fault core strands, defining the damage zone. Macro-scale deformation elements within the damage zone include simple mode I fractures, shear fractures, and fractures with more complex, branching morphology. Our results emphasise that fault zone architecture is variable between faults that developed in different tectonic settings. Geologic parameters applied to models of rupture propagation should therefore be qualified to relate to specific deformation conditions.

## **Application of airborne LiDAR to mapping seismogenic faults in forested mountainous terrain, southeastern Alps, Slovenia**

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Results are presented of the first airborne LiDAR survey ever flown in Europe for the purpose of mapping the surface expression of earthquake-prone faults. Detailed topographic images derived from LiDAR data of the Idrija and Ravne strike-slip faults in NW Slovenia reveal geomorphological and structural features that shed light on the overall architecture and kinematic history of both fault systems. The 1998  $M_W = 5.6$ , and 2004  $M_W = 5.2$  Ravne Fault earthquakes and the historically devastating 1511  $M = 6.8$  Idrija earthquake indicate that both systems pose a serious seismic hazard in the region. Because both fault systems occur within forested terrain, a tree removal algorithm was applied to the data; the resulting images reveal surface scarps and tectonic landforms in unprecedented detail. Fault breccia and gouge zones are easily discriminated by their textural expression. Oblique perspective views of the LiDAR data also reveal the attitude of folded bedding in steep terrain which was verified in the field. Importantly, two sites were discovered to be potentially suitable for fault trenching and palaeo-seismological analysis. This study highlights the potential contribution of LiDAR surveying in both low-relief valley terrain and high-relief mountainous terrain to a regional seismic hazard assessment programme. Geoscientists working in other tectonically active regions of the world where earthquake-prone faults are obscured by forest cover would also benefit from LiDAR maps that have been processed to remove the canopy return and reveal the forest floor topography.

## Characterization of normal fault curvature

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The study of 3D fault curvature offers new insights into the geometry of normal faults providing an enhanced understanding of the relationship between fault surface geometry and wall rock deformation. Characterizing normal fault curvature provides empirically derived geometric constraints that can be used to guide automated fault interpretation software.

Using examples from outcrops in SW England, the Aegean and northern Spain together with seismic data acquired from the Niger Delta, we apply a range of curvature calculations based on the techniques developed by Lisle (1994) and Bergbauer & Pollard (2003). Our results show that fault surfaces frequently display scale-independent 2D and 3D curved geometries including corrugations, elongate troughs and domes. Threshold values of curvature are described by a power-law relationship incorporating maximum observable 2D and 3D *Gaussian* curvature with the resolution at which the surface is sampled. This relationship will be used to assist the procedure of discriminating between realistic and unrealistic fault surfaces generated by automated fault interpretation software developed at the University of Birmingham.

In addition, we investigate the hypothesis that the translation of wallrocks over a fault surface exhibiting Gaussian curvature will bring about wallrock deformation resulting from divergence/convergence of particle motions paths within the surrounding rock volume. Wallrock fracture maps superimposed onto colour-contoured surface curvature maps suggest that the 3D geometry of a fault surface has the capacity to influence wall rock deformation in a quantifiable and predictable manner.

The enhanced understanding of fault geometry gained from this study has the potential to i) increase the efficiency of hydrocarbon recovery from compartmentalised reservoirs where permeability and fluid migration are strongly affected by faults and associated wall rock deformation patterns and ii) improve automated fault interpretation software by incorporating empirically derived geological constraints minimising the need for costly manual interpretation.

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## Experimental determination of yield parameters for a high porosity sandstone

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The mechanical properties of Hollington sandstone, a weak but cohesive sandstone with average grain diameter ( $R$ )  $\sim 200\ \mu\text{m}$  and porosity ( $\Phi$ )  $\sim 28\%$ , have been investigated. Hydrostatic and constant displacement rate triaxial experiments were conducted at a constant pore pressure of  $\sim 16\text{MPa}$  and at a range of confining pressures up to  $400\text{MPa}$ . A servo-controlled pore volumometer was used to track porosity changes during the deformation. Acoustic wave velocities were also measured as a function of failure under hydrostatic confining pressure.

Hydrostatic loading experiments showed three distinct regions of deformation; (1) non-linear compaction, (2) linear (elastic) compaction, (3) hydrostat deflection at a critical pressure ( $P^*$ ) of  $238\text{MPa}$ , beyond which irrecoverable compaction occurs. Permanent porosity loss on the order of  $3\text{-}6\%$  was observed at effective pressures up to  $400\text{MPa}$ . Microstructural observations show that pervasive brittle grain crushing is the cause of irrecoverable compaction. A Hertzian contact model provided a good estimator of  $P^*$  given  $\Phi$  and  $R$ . The onset of permanent pore collapse is represented in the seismic velocity data as a transient decrease in velocity, due to the sudden creation of a high crack density, followed by resumption of increasing velocity with pressure as the rock stiffens. Triaxial tests showed capped yield surface behaviour typical of soils and porous weak sandstones. A plot of the yield data, expressed as differential stress  $Q$  versus effective mean stress  $P$ , produces approximately circular yield envelopes that increase in size with decreasing porosity. Deformation at pressures above the critical state line is macroscopically ductile, with marked work hardening as the porosity collapses and the rock stiffens, until a constant flow stress at constant volume is attained when the material reaches the critical state. We have also investigated the yield behaviour at effective pressures beyond  $P^*$ , when a second cycle of increasing yield stress under differential loading occurs in the damaged material.

Study of natural flow of rocks under shallow crustal conditions has been generally neglected, perhaps because hydrothermal cementation tends to 'repair' the crack damage. It is of considerable importance in porous hydrocarbon reservoirs, because there have been many instances of surface subsidence in hydrocarbon fields as effective pressure is increased through fluid withdrawal, leading to porosity collapse and enhanced sand production. Thus understanding the effects of hydrostatic and differential loading on failure in porous sands can be of considerable economic importance.

## **Shear bands and fracture systems in granular materials - A numerical study.**

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Our objective is to understand the microstructural rearrangements associated with the localization of deformation into shear zones. This objective remains a critical geological issue. Fluid flow paths are controlled by such rearrangements through the effects of volume change and associated changes in the stress field. Geochemical reactions, and hence mineralogical changes, which result from interactions between fluid flow and the rock mass the fluid flows through, will occur in different patterns, controlled by these fluid flow paths.

In contrast to continuum systems where localisation or shear band development arises through a bifurcation in a predefined system of differential equations, shear bands emerge in numerical simulations of deforming granular systems with no prescribed mathematical relations other than very simple contact forces between particles together with the boundary conditions. Shear band emergence arises from the self-organisation of large numbers of particles with long-range geometrical interactions playing a dominant role. As such, both translation and rotation of particles is important with particle rotation playing a fundamental role. Granular media therefore deform more like materials with non-local constitutive relations than materials where only first order interactions are relevant. In large systems far from equilibrium a continuum approach would say that the dissipation of energy plays a fundamental role in defining the evolution of the system including whether the evolution is unstable or not.

Here we adopt a thermo-mechanical approach and explore the fluxes of energy in the evolving granular system (that has cohesion between the particles) as it is loaded through the unstable localisation regime and track the evolution of energy dissipation. The sign of the second order work defines the emergence of instability in the system. Initially these instabilities decay into stable configurations of particles but with continued loading, force chains collapse locally to generate geometrically necessary fractures. These localised zones then propagate to generate what are identified as localisation zones and as what are expressed ultimately as the percolation thresh-hold for broken bonds. However, long before this stage, the second order work fluctuates between positive and negative in bursts with weakly correlated bursts in kinetic energy as damage continues to grow. This behaviour suggests that any continuum constitutive description of granular behaviour must be (i) non-local in an anisotropic manner, (ii) micropolar and (iii) involve damage evolution. We discuss how such a continuum approach might be implemented in order to model large scale systems.

## **Kinematics and microstructural development of a high grade shear zone, Lewisian Gneiss, NW Scotland**

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Combined structural and metamorphic studies are essential to understand the microstructural and rheological development of high strain zones. This study examines one such zone, exposed on a promontory south-west of Inveralligin, which forms part of the larger Torridon shear zone within the southern Lewisian Gneiss complex. Proterozoic deformation and metamorphism have resulted in a shape fabric, defined primarily by quartz aggregates, and a transposed location fabric defined by quartz-feldspathic and mafic layers containing hornblende or biotite and epidote. Field data show that the 10m scale shear zone has a normal sense of movement which provides a kinematic framework to investigate the microstructural evolution of the gneisses.

Within the shear zone, two amphibolite Scourie dykes have been isoclinally folded. These dykes are currently on the order of 50cm thick and show a similar style of folding with thickening of the hinge, which are parallel to the stretching lineation defined by elongate felsic aggregates. Hornblende in these dykes shows both crystallographic and shape preferred orientations (CPO & SPO) and the plagioclase, while having a weak SPO, is strongly concentrically zoned. The rocks within this shear zone have undergone considerable deformation since dyke emplacement. This is attributed to the 'Laxfordian' episode rather than the pre-dyke 'Inverian' event although Laxfordian structures are usually considered to have a larger strike-slip than dip-slip component. Evidence from this shear zone suggests that the kinematics of the Laxfordian event are not just straight forward strike-slip.

The mineralogy of the gneisses is variable with some lithologies containing epidote and biotite and others containing hornblende. Generally, hornblende and microcline are mutually exclusive but one sample where they both occur shows evidence of a reaction producing biotite and epidote. Other lithologies contain no hornblende or microcline and are dominated by plagioclase and quartz with distributed grains of biotite. In all these rocks, the plagioclase is zoned, both concentrically and in more complex patterns, and the quartz, with which the plagioclase is intimately mixed, occurs as elongate grains with well developed sub-structure. Evolutionary models for this shear zone must explain the ubiquitously zoned plagioclase within rocks of differing mineralogy and therefore one, or a combination of the following factors: bulk composition, metamorphic grade, or extent of reaction.

The presence of plagioclase CPOs in a number of samples is consistent with dislocation creep being the dominating deformation mechanism as is usually considered the case in the lower crust. However, in other samples the plagioclase does not have a CPO, supporting deformation by diffusion creep, but show similar microstructures and zoning patterns. This apparent mixture of deformation mechanisms suggests a complex spatially and temporally evolving rheology for high grade shear zones.

## **Experimental dehydration of serpentinites: effects on mechanical behaviour**

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Dehydration of serpentine releases ~13 wt % water and generates up to 25 % porosity due to the reduction of volume of solids across the reaction. Provided sufficient fault leakage to avoid the development of pore overpressures, the mechanical behaviour of the resultant rock will be determined by the generated large porosity. To explore how this influences rock strength we run a series of shortening experiments under drained conditions on previously dehydrated lizardite-serpentinites. We measured water expelled by compaction either during hydrostatic loading or during differential shortening by means of a servo-controlled volumometer. Under non-hydrostatic loads, samples yield ductilely at relative low stresses, but still higher than those expected for talc, followed by a stage dominated by continuous strain hardening. Although there is evidence that talc deforms plastically and may help accommodate part of the shortening, a significant part is due to the collapse of the porosity, which produces the strain hardening during compaction. Experimental results indicate that dehydrated serpentinites are too weak to concentrate high stresses and therefore would be unable to nucleate large earthquakes. Neighbouring rocks in the mantle above or in the lithosphere below would probably be strong enough to hold high stresses very likely to be released by brittle failure with the influx of water expelled by dehydration and/or compaction in serpentinites.



## Deformation of the Earth's lower mantle: insights from analogue materials

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(Mg,Fe)SiO<sub>3</sub> perovskite is considered to be the most abundant phase in the Earth's lower mantle, along with magnesiowüstite and other minor high pressure phases. Therefore knowledge of the rheological properties of (Mg,Fe)SiO<sub>3</sub> is crucial to the understanding of the rheology of the lower mantle. Presently, deformation experiments, yielding reliable rheological data, cannot be performed within the stability field of (Mg,Fe)SiO<sub>3</sub> perovskite. Fortunately, many elements can combine to form the perovskite structure and hence an analogue for (Mg,Fe)SiO<sub>3</sub> perovskite that is stable at experimentally tractable conditions can be found. (Ca,Sr)TiO<sub>3</sub> is one such material, which is stable at atmospheric pressure, and undergoes two structural phase transitions between 100 and 1600 K depending on the Ca:Sr ratio. By studying the deformation behaviour of (Ca,Sr)TiO<sub>3</sub> some insight can be gained in to the rheological properties of (Mg,Fe)SiO<sub>3</sub> perovskite. Polycrystalline samples of (Ca<sub>0.9</sub>,Sr<sub>0.1</sub>)TiO<sub>3</sub> have been synthesized from high purity oxides yielding samples with <3 % porosity and a grainsize of ca. 100 µm. These samples have been used to study the rheological properties of the tetragonal and cubic phases. Data from compression experiments performed over a temperature range spanning the orthorhombic to cubic phase transition show a power-law rheology with a stress exponent of ~4 and an activation energy of ~600 kJmol<sup>-1</sup>. A crystallographic preferred orientation develops, in the compression experiments, that is consistent with [110] slip. (Ca<sub>0.9</sub>,Sr<sub>0.1</sub>)TiO<sub>3</sub> samples deformed in the cubic stability field to high strain in torsion show a comparable strength to compression tests under the same conditions. In these high-strain torsion experiments there is no shape preferred orientation of the grains consistent with the shear strain. Despite this lack of a shape fabric a crystallographic preferred orientation develops that is consistent with [100] slip. Lattice rotations towards the rims of grains are observed to be about an axis perpendicular to the shear direction in the shear plane. It is thought that these samples are deforming by grain boundary sliding, probably accommodated by components of both diffusion and dislocation creep.

## **Dual petrological and strain-path controls on the seismic anisotropy of deformed continental crust**

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Recorded seismic anisotropy due to lattice preferred orientation (LPO) of elastically anisotropic minerals (especially micas and amphiboles) may be interpreted in terms of strain trajectories in deformed continental crust. Such usage assumes that LPO and seismic anisotropy indicate foliation and lineation. This assumption is tested using plausible rock compositions, microstructures and strain ellipsoids typical of different 3D strain paths to predict the in situ seismic response of deformed crust. For typical polymineralic lithologies, the bulk seismic anisotropy depends upon individual mineral modal content and LPO modulated by the single crystal elastic properties. Here we assume single foliations that parallel components of the 3D strain trajectories. Content can be varied progressively and proportionately for constant LPO to investigate how changing composition impacts on seismic anisotropy. Such ‘rock recipes’ indicate large seismic anisotropy values for micaceous rocks (e.g. schists) and smaller seismic anisotropy values for mafic middle-to-lower crust compared to felsic middle crust. Although deformation impacts also on LPO, the relative strengths of planar and linear features may not be recognised, with concomitant implications for seismic anisotropy, as shown via modified Flinn Plots. Both micas and amphiboles appear sensitive to finite strain, rather than infinitesimal strain, strain magnitude and strain path. For micaceous rocks, LPO and the resultant seismic anisotropy chart the orientation of the XY plane (foliation) but do not record the complete intensity or shape of finite strain ellipsoids. In contrast, amphibole-rich rocks generate seismic anisotropy that give a complete (XYZ) description of 3D strain trajectories. The strain attributes are key for establishing the structural geometry of deformed terrains and underpin traditional kinematic studies at outcrop. The challenge now is to take these methods into the subsurface using seismic anisotropy as a proxy for different deformation states.

## **Faulting in non-plane strain: transtension in the Coso region, California.**

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Vertical plane-strain extension in the brittle crust poses no kinematic problems in the rotation of fault blocks about horizontal axes because the blocks are bounded above by air or water and below by ductile lower crust. Only rarely, block rotation in horizontal plane-strain can be accommodated by changes in the geometry of zone boundaries and terminations, such as a retreating subduction zone. A major problem of structural geology is how general horizontal plane strains and non-plane (uniaxial, and triaxial) strains in the brittle upper crust are effected by fault systems. Transtension generates noncoaxial constriction ( $k > 1$ ) with a horizontal vorticity and poses difficult kinematic compatibility problems (our problems not nature's) of wrench/normal fault-combination block rotation and strain. Normal faults rotate around vertical and horizontal axes to give oblique slip, and wrench faults rotate around vertical axes. Problems arise, also, because blocks of varying size and shape bounded by normal and wrench faults rotate at different rates about vertical and horizontal axes while shortening or lengthening. Compatibility problems may be solved by block margin deformation, by bulk block strain, by buckling of faults, by volume increase with holes opening at block intersections, by alternating periods of normal and wrench faulting, by vertically and horizontally-stacked discrete arrays of normal and wrench faults. Multiple generations of faults result from fault rotation into orientations no longer favourable to slip and to bulk strain axis switching at high strains where the transport direction is at less than  $20^\circ$  to the zone boundaries. Further kinematic complexities arise in transtensional zones in which the zone boundaries are non-parallel, where strain is inhomogeneous, and where strain and displacement are partitioned.

The Coso transtensional region, in southern California is active, the horizontal strain rates are high, and there is a huge amount of seismic, heatflow, fluid flow, and borehole and surface geologic data. Between the Sierra Nevada and the Argus Range, the transport direction (from GPS) is roughly NNW at about  $10 \text{ mma}^{-1}$ . This generates triaxial constriction with an instantaneous stretching direction roughly WNW and a horizontal strain rate of about  $10^{-14} \text{ sec}^{-1}$ . Constriction is modeled by a combination of NNE normal faults, NE wrench faults, and WNW folds and thrusts, which rotate clockwise with vorticity, and NNW wrench faults, sub-parallel with the zone boundaries, that rotate very slowly counterclockwise against vorticity, a pattern of faulting, folding, and bulk strain recorded closely by fault slip data from earthquakes and field observations. In deformation zones generally, GPS and moment tensor sum data indicate very smooth velocity fields, which in turn means that the commonly accepted view of the rotation of large rigid blocks about vertical axes cannot be correct; instead, the upper crust behaves as a "continuum rubble" of very small "blocks".

## Extrusion and vorticity

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The deformation in the deep parts of orogenic belts as exemplified by the Lewisian gneisses of NW Scotland is difficult to fit into compatible models based mainly on simple shear, and the author of this contribution has too often argued against mixing pure shear and simple shear on the grounds that pure shear component would require extrusion. Recent geodetic measurements in the Himalayas have shown that extrusion does indeed take place and that it is the best source of deformations which are mixtures of pure and simple shear, that is of deformations with kinematic vorticity numbers different from 1.0. I digitized the GPS velocity data of Zhang et al. (Geology: 32, 809-812, 2004, from which I was able to determine the shearing velocity gradients. I estimated the E-W strain-rate to be  $1.41\text{E-}08 \text{ yr-1}$ , and the N-S strain rate as  $-1.8\text{E-}08 \text{ yr-1}$ . Using an assumption of no rate of volume change gave  $3.9\text{E-}07 \text{ yr-1}$  for the vertical strain-rate. This enabled the construction of the velocity gradient matrix. In idealized extrusion strain material is squeezed out symmetrically producing a roughly parabolic velocity distribution with maximum velocities growing from zero at the plane of symmetry to ever larger values away from that plane. The data of Zhang et al., (2004) give transpressive kinematics with values of the kinematic vorticity number ranging from 0.0 to  $\pm 0.42$ . Ideal simple shear is 1.0.

I integrated the velocity gradient matrices over 12 Myrs giving finite strain in terms of intensity (ratio of greatest to least principal stretch), ellipsoid shape (the K value) and the orientation of the normal to the plane of greatest flattening. The plane of greatest flattening is always vertical, meaning that any fabric produced would be vertical. It is oriented with a strike parallel to N110E where the vorticity number is low, but deviates up to  $\pm 20^\circ$  where the vorticity number is higher. The intensity of strain varies from 1.5 where vorticity is zero to 1.7 in the regions of high vorticity. The ellipsoids K values are in the region of 0.45, corresponding to a slightly prolate shape, which is the result of the small vertical extension.

The finite strain orientation and intensity provides an explanation for the strain states, structures and fabrics of many parts of the Lewisian. This supports a conclusion that tectonic extrusion is may be a frequently occurring phenomenon throughout geological history and provides the sort of compatible deformation which involves varying kinematic vorticity numbers.

## **The extension discrepancy at non-volcanic margins: depth-dependent stretching or unrecognised faulting?**

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Rifted margins show an apparent discrepancy between the amount of extension measurable from faults ( $\beta_f$ ) and the amount of crustal ( $\beta_c$ ) or lithospheric thinning determined from wide-angle data or subsidence;  $\beta_f$  is commonly far less than  $\beta_c$ . This extension discrepancy has commonly been interpreted in terms of depth dependent stretching (DDS) in which the upper crust is extended and thinned far less than the rest of the crust. However there are some problems with this idea. First, the magnitude of the discrepancy would require that at some margins the entire crust is thinned to well below 5 km without significant brittle extension of the upper crust, which would seem mechanically difficult. Second, assuming that the total amount of extension across a margin is the same at all lithospheric levels, any extension discrepancy must be balanced by an equally significant inverse discrepancy somewhere: these have not been reported. Finally, detailed velocity structures from conjugate or close to conjugate non-volcanic rifted margins of the North Atlantic show that upper crustal thinning closely follows thinning of the whole crust. This implies that these margins display no significant crustal depth-dependent stretching.

An alternative is that the extension discrepancy arises from the failure of the seismic method and of the seismic interpreter to identify all the brittle extension of the upper crust ( $\beta_{uc}$ ). In other words that  $\beta_f \ll \beta_{uc}$ . Distributed deformation too small to be resolved seismically is not sufficient, but major faulting may not be recognised if the faults have been rotated and/or dismembered during progressive extension. I show that both polyphase faulting and large-offset top basement faults rotated toward or beyond horizontal are present at some rifted margins, but are difficult to interpret, particularly on time migrations.

In conclusion the extension discrepancy at North Atlantic non-volcanic rifted margins is not due to DDS but represents the failure of the interpreter to recognise all the extension of the upper crust. It is likely that the same conclusion applies to other rifted margins.

## Strain estimation from fault-slip data

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Fault-slip analysis uses orientation data collected from mesoscopic faults and their associated slip directions to infer some properties the palaeostress tensor. This type of analysis has been developed and refined over two decades and has found widespread application in regions dominated by brittle deformation. Although this approach has often produced consistent results both regionally and with those from other stress gauges, some authors have questioned the validity of the technique for stress estimation. Critics of the method point out that the data from fault displacements relate more closely to strains than to stresses, and that interpretations in terms of stress requires additional assumptions (e.g. mechanical isotropy, small strains) to be made.

In this context we formulate the fault-slip problem in terms of strain. We assume that

- 1) the bulk strain, the overall strain at a sampling station, is due entirely to slip on variably oriented fault planes,
- 2) such strains, although clearly inhomogeneous, can be analyzed using the concept of the strain ellipsoid on the scale of the sampling station.
- 3) slip on individual faults occurred in the direction corresponding to that of the shear strain expected from the fault plane's orientation in relation to the bulk strain ellipsoid.

For available data consisting only of the orientations of several faults and their lineations, we show how the orientations of the principal strains can be estimated, together with a parameter  $F$  describing one aspect of the strain ellipsoid's shape, where  $F = (\sigma_1 - \sigma_2) / (\sigma_1 - \sigma_3)$ , and where  $\sigma_1 > \sigma_2 > \sigma_3$  are the principal stretches (new length/old length). The method is illustrated using data from the Boso Peninsula, Japan.

Data consisting solely of orientations do not allow the estimation of the magnitudes of the principal strains. Additional measurements of fault spacing and displacement are required for deriving principal strain magnitudes.

## How is extension distributed in the upper crust?

Martin W. Putz\*, David J. Sanderson

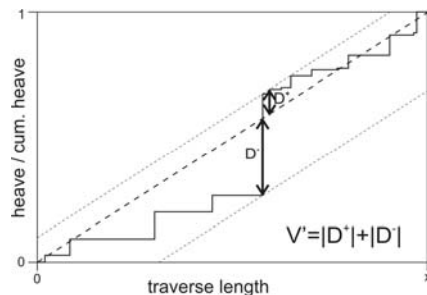
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Displacements on extensional structures belonging to the same tectonic phase have been measured over 6 orders of magnitude at two localities. The examined structures range from faults with several hundreds of metres displacements down to micro-fractures with <0.1mm aperture. The study is based on a variety of line-samples ranging from 10m to 16km in length and is designed to capture the spatial distribution of extension across the entire scale range. This allows examination of both the spatial heterogeneity and scaling relationships for normal faults and tensile fractures.

One of the two study areas is dominated by mudstones with only few interbedded carbonates; the other by m-thick carbonates with interbedded mudstones. Early deformation in the two lithologies seems to be accommodated in very different ways. The mudstone-rich sequence shows an early, almost continuous, low background strain across the region, whereas the limestone-rich sequence shows no measurable background strain. Tensile fractures in the latter mainly opened during early strain localisation within narrow zones later breached by faults as extension increased. The ratios between damage zones and virtually undeformed background regions are about 1:3 and 1:5 in the mudstone and limestone rich sequences, respectively. The extent of the damage zones in the wallrocks appears to be largely independent of the displacement on the fault (typically 15m in mudstone and 3m in limestone rich rocks) and is interpreted as being mainly caused by early localization rather than by kinematic damage due to slip on the fault.

To quantify the degree and statistical significance of heterogeneity at different scales we apply a non-parametric method based on Kuiper's test of cumulative plots.



*Kuiper's Test:*

*The solid step curve is the cumulative heave, the straight dashed line represents a uniform distribution, the two dotted lines indicate an "envelope" defined by the maximum deviations from the uniform distribution above ( $D+$ ) and below ( $D-$ ). The test statistic is the quantity  $V' = |D+| + |D-|$ , which varies from 0 (homogenous) to 1 (heterogenous).*

In the mudstones thinner veins (0.1 – 10mm thickness) are homogeneously distributed, but thicker veins (10-100mm thickness) accommodate a markedly heterogeneous strain. Similarly strain taken up by faults with lower displacements (0.5 – 100m) is fairly homogeneous, but more heterogeneous on the largest faults. In the limestone-rich sequence, vein-strain is heterogeneously developed whilst fault-strain is fairly homogeneously distributed.

We conclude that strain is accommodated in a scale dependent manner and that it is not possible to extrapolate fracture frequencies and strain from fault scale to vein scale in layered sequences.

## Plenary lecture - Anatomy of an ancient earthquake from an exhumed fault

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Pseudotachylytes (solidified friction-induced melts) decorate some exhumed ancient faults and remain, up to now, the only fault rocks recognized as the unambiguous signature of seismic slip. It follows that pseudotachylyte-bearing fault networks might retain a wealth of information on seismic faulting and earthquake mechanics.

In this contribution, we will show that in the case of large exposures of pseudotachylyte-bearing faults (as is the case of the 30 Myr old Gole Larghe Fault exhumed from a depth of  $\sim 10$  km and cutting the Adamello tonalites, Italian Alps), we might constrain most of the earthquake source parameters by linking field studies with microstructural observations, high-velocity rock friction experiments, modeling of the shear heating and melt flow, and dynamic rupture models.

In particular, it has been possible to estimate the rupture directivity, the slip weakening distance, the fault dynamic shear resistance, the traction evolution with slip and the ratio between surface energy and frictional heat.

We conclude that the structural analysis of an exhumed fault may allow the reconstruction of the earthquake mechanics and the seismic energy budget at a given point of the fault.



## **So what does the Moine Thrust actually do? Correlating the Torridon and Morar groups across the Moine Thrust, NW Scotland.**

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The Early Neoproterozoic Morar and Torridon groups in Northern Scotland are both dominated by siliciclastic deposits, several kilometres thick. They are now separated by the Moine Thrust, whose character is obviously dependent on the pre-Caledonian relationship between the two sequences. Equivalence has been suggested in the past, but is generally not accepted. In the Northern Highlands, the Applecross and Aultbea Formations (Torridon Group) and the Altnaharra Formation (Morar Group, lowest part of Moine Supergroup) are compared. New work on the Altnaharra Formation has revealed a stratigraphical thickness of 3-5 km of uniform coarse, gritty psammite, with bed thickness 0.1 to 5 m, abundant cross-bedding, nested trough cross-bedding and locally abundant soft sediment deformation structures. Palaeocurrents suggest eastward flow. These characteristics apply equally to the Applecross Formation. Both formations are interpreted as high-energy fluvial braided rivers deposits. Similarities in lithology, sedimentology, stratigraphical thickness, geochemistry, detrital zircon ages, age of deposition, palaeocurrent and unconformable position upon Archaean basement shows that the Torridon and Morar Group in the Northern Highlands can be directly correlated across the Moine Thrust. The west-ward displacement on the Moine Thrust is smaller than the length of the east-west flowing river system that deposited the sediments, making it unlikely that the two sequences developed in separate basins at separate times. The age of deposition overlaps with the waning stages of the Grenville orogen and the detrital zircons in the sediments can be linked to a source in the Grenville orogen. It is therefore concluded that (1) the Torridon and the Morar Group in the Northern Highlands are direct correlatives, and (2) both deposited in a trunk orogen-parallel foreland basin to the Grenville Orogen (analogous to the Ganges Basin) and finally (3) the Moine Thrust is not a terrane boundary; simply a magnificent thrust, repeating the same sequence – as thrusts commonly do.

## **Importance of multi-phase thrusting for tectonic reconstruction: Late Mesozoic – Early Cenozoic of Central Tauride Mountains, S Turkey.**

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A key issue is how to restore a thrust stack to determine the tectonic setting and palaeogeography of pre-existing rift, passive margin and oceanic units. In the E Mediterranean Tethyan region, palinspastic restorations generally assume a relatively simple in-sequence, piggy-back type thrust geometry, usually related to one main phase of emplacement. However, this may result in an unrealistically complex restored palaeogeography involving the emplacement of several different oceanic and continental margin-type units in a geographically small area.

To resolve this we are currently studying the Beyşehir-Hoyran-Hadim (B-H-H) nappes in the central Taurides, S Turkey. The area includes an autochthonous continental platform of Late Precambrian-Early Eocene age (Geyik Dağ), overlain by allochthonous Late Palaeozoic-Early Cenozoic units (B-H-H). These include emplaced platform, slope and deep-marine sediments, and ophiolitic units that were all emplaced southwards over the relatively autochthonous continental platform ('Tauride microcontinent') prior to Late Eocene. In general, the ophiolitic and distal margin units (Beyşehir-Hoyran nappes) are located at a low level in the thrust stack compared to large slices of platform lithologies (Hadim nappes) near the top. A simple in-sequence restoration would imply the existence of continent passing northwards into a small oceanic basin, and then into a tiny microcontinent followed by a larger oceanic area to the north. However, the Beyşehir-Hoyran nappes are compatible with a single N-facing rifted continental margin/ocean transition (Andrew and Robertson 2003).

We have collected a large amount of structural data from the thrust stack for over 300km along strike. Observations of the nappe stacking order and nature of contacts are supported by evidence from macro and micro folds, thrust duplexes, fault planes, stretching lineations and shear fabrics. In addition, syn-tectonic sediments record thrust emplacement and foredeep development during Late Cretaceous (pelagic limestones and polymict debris flows) and Eocene (terrigenous turbidites and debris flows).

The combined data show that the nappes were emplaced in two phases: 1. During the latest Cretaceous (Maastrichtian) distal continental margin and ophiolitic units were emplaced southward onto the relatively autochthonous carbonate platform (i.e. thin-skinned emplacement); 2. During the Mid-Eocene, thrusting cut down into deeper levels of the autochthon and large slices of Palaeozoic "basement" (Hadim nappe) were thrust southwards above units emplaced during the initial, Upper Cretaceous phase (thicker-skinned emplacement). Late-stage internal re-imbrication, backthrusting and strike-slip modified the local thrust geometry but did not fundamentally change the two-phase stacking geometry.

Taking account of regional evidence, the first-phase latest Cretaceous emplacement was related to the collision of a N-dipping subduction zone with a rifted passive margin driving ophiolite and passive margin emplacement (i.e. soft collision). The second phase (mid-Eocene) reflects final suturing of the N Neotethys ("hard collision"). In conclusion, the nappes restore as a relatively simple Mesozoic rifted margin, passing northwards over a deep-water margin into the N Neotethys with implications for other comparable regions (e.g. Balkans, SE Asia)

## **Thrusts, mullions and culminations in the Moine rocks of south-west Sutherland, Scottish Caledonides.**

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The Ben Hope and Achness Thrusts and associated ductile structures deform Neoproterozoic Moine metasedimentary rocks in south-west Sutherland. The Moine rocks are deformed by a higher structural manifestation of the familiar Assynt Culmination, of comparable scale and complexity, lying structurally above and to the ESE in the hanging wall of the Moine Thrust. The Ben Hope and Achness thrusts converge downwards onto the Moine Thrust at the south-east corner of the Assynt Culmination, and the southern limit of the culmination in Moine rocks is revealed as a linear deformed zone accommodating lateral termination of the component thrust sheets.

The classical Oykel Bridge mullion zone lies directly along the axis of this lateral termination with fold and cleavage mullions arranged colinear with the regional top-to-the-WNW thrust transport direction. More specifically, the mullion structures are most prominently developed on the attenuated long limbs of kilometre-scale F2 folds which have been rotated and are now downward-facing in the lateral termination zone.

Structural evolution of the Moine rocks in the culmination is diachronous within a foreland-propagating system of ductile deformation such that, for example, the S2 fabric in the Achness Thrust Sheet is crenulated in the immediate hanging wall of the Achness Thrust, by an “S3” fabric that is continuous with the S2 fabric in the underlying Ben Hope Thrust Sheet. All of the fabrics observed in this culmination can readily be attributed to Scandian deformation, any Neoproterozoic deformation apparently leaves no imprint and may only be preserved as inclusion trails in early porphyroblasts.

## **Structural style of the eastern Kalachitta Range, lesser Himalayas, N. Pakistan**

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The Eastern Kalachitta Range (EKR) makes the southern periphery of the hill ranges and occupies a very significant position in Lesser Himalayas by forming the northern edge of the hydrocarbon bearing Potwar Plateau. It lies in the hangingwall of Main Boundary Thrust. Structural studies of the EKR are carried out with the help of field mapping and TM image to determine its structural styles. The data is processed in a structural modelling program, 2DMove and a balanced section is constructed across the area. ILWIS GIS software is used to geo-reference and overlay different map types. This study shows that the structural style of the Eastern Kalachitta Ranges is “passive roof duplex structure” with lower and upper detachment levels. Thrusting controls the deformation between the upper and lower detachment levels and the area is characterized by minor brittle shortening. The oldest stratigraphy involved with the emergent thrust faults is Samana Suk Formation indicating that the basal detachment lies at the base of Samana Suk Formation and the upper detachment lies within the Patala Formation. The overlying Eocene formations are not affected by the thrusting but the upper detachment has caused them to fold and lift above. The folding controls the structures above the upper detachment level. The area shows progradation of thrusting towards the foreland and this deformation produces complex geometry of stacked folds. The southern part of the study area lying in the footwall of Main Boundary Thrust, is dominated by detachment folds and their detachment lies within the Patala Formation, which has flowed in core of these folds. Making use of the restoration technique of the 2DMove program, the horizontal shortening calculated in the area is approximately 25-km.

## A Rheic cause for the Acadian deformation in Europe

Nigel Woodcock<sup>\*1</sup>, Jack Soper<sup>2</sup> and Rob Strachan<sup>3</sup>

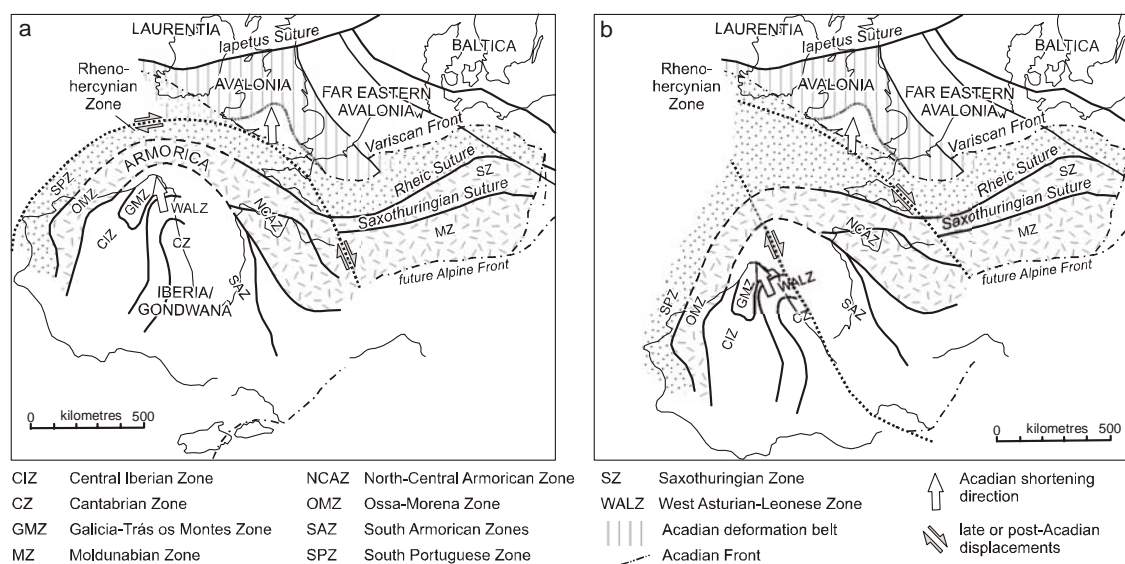
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The Acadian (mid-Devonian) deformation in northwest Europe has typically been interpreted as the culminating event of the Silurian closure of the Iapetus Ocean. This view has been challenged by the recognition of an intervening early Devonian transtensional event across part of the assembled Laurussian continent. Instead, the Acadian shortening must be driven by a renewed 'push from the south', involving subduction of the Rheic Ocean, and either flat-slab subduction or impingement of another Gondwana-derived continental fragment. A major problem with either hypothesis is the lack of Acadian deformation or even correlative unconformity in the segment of the Rhenohercynian Zone between the Acadian belt and the Rheic suture. The possibility is explored that this Rhenohercynian segment was juxtaposed with the Acadian belt and the Midland Microcraton during latest Acadian and, or, Variscan tectonics. If so, a major lithospheric suture must lie buried just south of the Variscan Front, along the Bristol Channel Fault Zone, and the missing Acadian terranes must now lie elsewhere along the orogen. A case is made that they are related to, if not represented by, the allochthonous terranes of northwest Iberia. Whatever, the Acadian event in Europe should properly be regarded as proto-Variscan rather than late Caledonian.



Two hypotheses for removal of major late Acadian or Variscan dextral strike-slip on the Bristol Channel-Bray Fault Zone. In model (a) the Ibero-Armorican promontory rotates back by 30° and becomes a plausible driver for the Acadian deformation

## **Alternative tectonic models for the Late Cenozoic evolution of Cyprus: New evidence from the southern part of Cyprus.**

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Three published tectonic models for the neotectonic setting of Cyprus currently exist i.e. (i) subduction/incipient collision, (ii) advanced collision and (iii) transpression/restraining bend. In the first model (favoured here) a subduction zone, the 'Cyprus Arc', existed between the Eratosthenes Seamount and the S coast of Cyprus. Subduction was initiated in the Mid-Miocene (c. 15 Ma). Extension in the overlying plate formed sedimentary basins and was caused by retreat of the trench ('roll-back'). The Eratosthenes Seamount then collided with the trench in the Pliocene (c. 3Ma), obstructing subduction and initiating rapid uplift of the island. In the second model, involving more advanced collision, south-verging, thick-skinned, linked imbricate thrusts (e.g. the 'Paphos Thrust') formed at depth near the 'Cyprus arc', between the Kyrenia Range to the N (the Kyrenia fold/thrust belt) and the Eratosthenes Seamount in the S. The present thrust geometry dates from the Eocene (c.45 Ma) when imbricate thrusting first began in the 'forearc', forming a 'Troodos-Larnaca culmination'. In the third model, a system of left-lateral faults exists between two restraining blocks, the Kyrenia Range and the Eratosthenes Seamount, which controlled the uplift of the Troodos massif. The Neogene-recent was dominated by transpression as Cyprus was extruded westwards related to the 'tectonic escape' of Anatolia.

To test these tectonic models we have investigated the Neogene-Recent tectonic and sedimentary evolution of S Cyprus; combining field studies, palaeomagnetic and luminescence dating techniques with remote sensing methods (satellite imagery and aerial photography). Fault planes (n=c.1000) cutting Neogene sediments in S Cyprus (W of Limassol) mainly exhibit a NNE-SSW trend, whilst those in SE Cyprus (E of Limassol) trend NE-SW. When present, kinematic indicators (fault offsets and slickensides) almost entirely indicate normal faulting W of Limassol. One apparent anomaly, however, is the existence of a large (several km) overturned, to recumbent, fold structure (SW facing) affecting Quaternary terrace sediments in the SW coastal area (near Kouklia and Ayia Marinoudha). This feature could be interpreted either as the result of seaward gravity sliding above late Cretaceous bentonitic clay, or as thrusting related to localised compression/transpression. In SE Cyprus Neogene-Quaternary deposits are dissected by left-lateral fault lineaments (i.e. at Kolossi and Cape Kiti). Some of these faults re-activate compressional structures of probable Miocene age. Further N, observed faults in the Arakapas Fault Zone (Limassol Forest) are variably orientated, but generally trend E-W, mainly reflecting late Cretaceous and Miocene tectonics. In the absence of Quaternary sediments in this area significant faulting of this age could not be confirmed. In addition, magnetostratigraphic data allow Plio-Quaternary sediments to be correlated in several areas (SW coast and Mesaoria plain), and indicate that differential vertical uplift has occurred in the SW coastal area (Pissouri area) from the Pliocene onwards.

We conclude that model 1: i.e. Neogene subduction/incipient collision fits our data better than Model 2 (advanced collision) or model 3 (transpression/restraining bend).

## **A model for the structure and origin of mud volcano craters: examples from eastern Azerbaijan and the South Caspian Sea**

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A mud volcano crater is defined as a circular depression found at the summit plateau of large flat-topped mud volcano edifices. Field mapping and seismic reflection analysis of active mud volcanoes in Azerbaijan and the South Caspian Sea have found these craters to consist of a number of common structural and geomorphological elements. These similarities together with the clear imaging and exposure of each example enable a model of typical crater structure to be presented. Included in the model is a subcircular crater rim that defines the topographic boundary of the crater, a crater margin fault, a marginal depression and a series of intra-crater extruded deposits. Similar crater structures are observed at a number of volcanoes within and outside the Caspian region indicating that the model may be of broad applicability to other mud volcanoes that develop circular craters. The model therefore provides a list of terms and a structural framework that may be useful to those describing and comparing mud volcano craters from within and outside the Caspian region. In addition, the close similarity of our model to those for the structure of magmatic calderas indicates the potential analogue value of mud volcanoes to the study of igneous volcanism.

The mechanisms of crater formation remain unclear although insights from 3D and 2D seismic reflection images suggest one possibility to be the upward propagation of a circular feeder system fault zone to the surface. Another is the volume loss resulting from the remobilization of previously erupted sediment sourced either from a buried and extinct edifice or from within the presently active edifice itself. An origin relating to gravitational collapse or mass movement is deemed unlikely due to the circularity of the crater margin fault and the lack of any indicators of strike-slip displacement along the lateral crater margins.

## **Intrusive domain of the Koturdag mud volcano system, Azerbaijan**

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Intrusive domains that connect kilometre-scale extrusive mud volcanoes to their autochthonous source are very poorly documented, even though their extrusive edifices can be spectacular geomorphological features or geohazards like the 2006 eruption in Sidoarjo, Java. Here we report the hunt for and discovery of an exhumed intrusive domain within the area of kilometre-scale extrusive mud volcanoes onshore Azerbaijan.

Why look for intrusive domains onshore Azerbaijan, which has long been regarded solely as an area of extrusive, Recent mud structures? Much of onshore Azerbaijan has been uplifted approximately one kilometre since the Pliocene. Exhumed strata include lateral equivalents of offshore strata that are imaged on seismic reflection data as having been contemporaneous with mud extrusion. This indicates that Tertiary mud volcanoes may have been uplifted and eroded in the onshore area, perhaps exposing intrusive domains. But was there pre-uplift volcanism in the onshore area? The driving mechanism of mud volcanism is considered to be overpressure in the autochthonous source layer – that volcanism is active today, after a kilometre of exhumation, suggests this driving mechanism would have been effective pre-uplift.

Koturdag mud volcano is one of several that occur along the hinge of the frontal anticline structure of the south Caucasus thrust system. The main mud volcano is a kilometre-scale extrusive cone that is still active today, producing kilometre-scale flows. Adjacent to the extrusive edifice, fluvial erosion has cut a canyon that exposes the country rock substrate of the extrusive material. This canyon shows that the Recent Koturdag extrusive material sits on a deeply eroded anticline and we infer that, as expected, extrusive domains in exhumed areas sit on beheaded intrusive domains.

A number of minor extrusive mud features outcrop directly on the bedrock walls of the badland topography in this canyon. Here we have a rare opportunity to see relationships between minor mud structures and the country rock. Invariably there is an intrusive relationship - mud gryphons and salse pools spill out on to strata that are in a range of structural attitudes. In some cases the mud leak points are associated with breccia pipes. The breccia is metre-scale blocks of xenolithic sedimentary strata (silts and sands) contrasting with the shaley host strata. We interpret this breccia as representing a paleo-diatreme, a record of the initial propagation phase of the intrusive system.

Our observations of a number of metre-diameter, steep pipe-like intrusions scattered over an area of several hundred metres, can be integrated with seismic reflection mapping of offshore structures in the Caspian, where we see calderas and structured country rock, but never any convincing direct observation of large-scale intrusions. We combine this work on and offshore Azerbaijan into a multiscale model of mud volcano systems.



## Potash values show Hormuz Island (Iran) to be a salt mushroom

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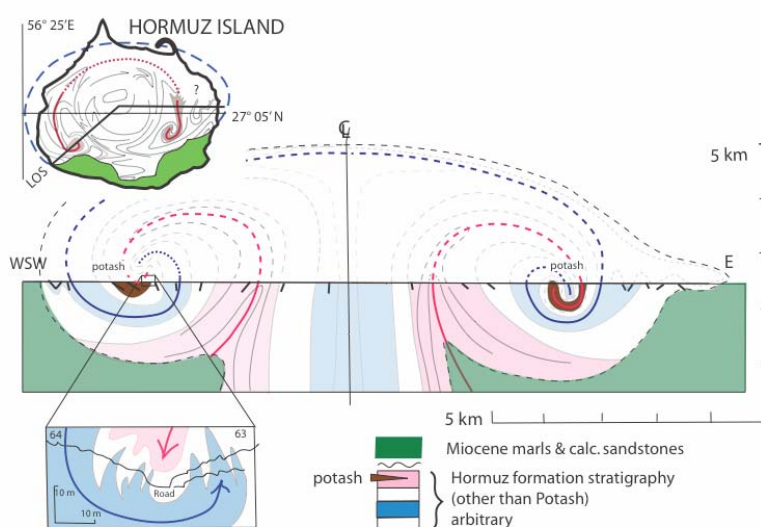
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Hormuz Island is the 7 x 6 km salt island that gave its name to both the strait at the entrance to the Persian Gulf and the Hormuz formation famous for its Neoproterozoic-Cambrian salt in and around the Gulf. About 200 diapirs of Hormuz salt have surfaced in the Zagros Mountains and its foreland basin since Triassic times.

In the last six years, the Potash Group of the Geological Survey of Iran has discovered increasing volumes of potash deposits in a small cluster of Zagros dapirs near the initial depocenter of the Hormuz salt. Whereas the potash in diapirs of Zechstein salt in Germany are repeated by complex curtain folds with vertical axes, those in most of this small cluster of diapirs are repeated by recumbent folds spread by gravity in high salt mountains. However, Holocene marine erosion removed most of these fountains and their recumbent folds in offshore diapirs and exposed deeper structural levels behind cliffs up to 100 m high. Potash values mapped by recent geochemical surveys on Hormuz Island are found in apparently unrelated patches- but have turned out to be a valuable “stratigraphic” marker in the strongly deformed salt.



Adding field measurements of the attitudes of compositional salt layering to concentric lineaments mapped on air photos and satellite images suggests that Hormuz Island consists of a mature mushroom-shaped diapir with its toroidal axis of rotation near the current level of exposure. Such a vortex is induced by shear between Miocene shales downbuilding around a column of salt that is still rising at c.6 mm/y. Parts of the margins of the salt may have been complicated by past gravity spreading. However, the surviving potash deposits are coiled in complex folds near the vortex axis implying that they were high in the initial Hormuz sequence. 2D numerical models simulate remarkably closely the exposed levels of the salt mushroom of Hormuz Island and suggest that it has a wide overhand above a narrow stem in this oil-rich region.

## Numerical modelling of rise and fall of dense layers in salt diapirs

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Salt layers and structures have been targeted as repositories for hazardous waste (e.g., Gorleben and Morsleben salt diapirs in Germany, WIPP site in USA, and Winschoten (Groningen), Netherlands). Gorleben salt diapir in NW Germany is currently used as an intermediate storage facility and has been targeted as a final repository for radioactive waste. Accumulations of evaporates in structures like Gorleben have formed from initially flat layers which were driven by differential loading during continued syn-kinematic sedimentation. Gorleben salt diapir has been used as a general guideline for our modelling of the rise and fall of dense blocks within salt diapirs. These blocks were initially embedded as a thick anhydrite layer (ca. 80m) within the upper half of the Zechstein Formation. Movement of salt stretched the anhydrite layer to boudins entrained in the rising salt.

We used 2D numerical models to study the entrainment of a dense anhydrite layer embedded within a buoyant viscous salt layer which was downbult by aggradation of frictional, non-Newtonian ( $n=4$ , constant temperature) sediments on the top of the salt layer. The diapir was triggered by a 400 x 150 m or 800 x 150 m wide block-like perturbation. Several parameters (viscosity of salt, sedimentation rate, stratigraphic position of anhydrite layers within the salt layer) were studied systematically to understand how the anhydrite layer is entrained. The numerical models demonstrate that sedimentation rate, viscosity of salt, width of the diapiric stem and stratigraphic position of the anhydrite layer are the parameters that influence entrainment of the initially horizontally anhydrite layer embedded within the salt. Based on models of salt diapirs we quantify flow rates and elucidate why inclusions rise accelerates and decelerates during diapirism. Anhydrite layers and blocks inevitably sink if the rise rate of the diapir is less than the rate of descent of the anhydrite layer or the diapir is buried by a stiff overburden.

## 3D seismic imaging of a Tertiary dyke swarm in the southern North Sea

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Dykes have rarely been interpreted using 3D seismic data and have only previously been interpreted in the southern North Sea using 2D seismic reflection data and magnetic modelling (Brown et al. 1994). This is due to dykes being predominantly vertical features in sedimentary basins, thus making them hard to image on seismic reflection data. Using 3D seismic reflection data we have analyzed the three-dimensional spatial distribution and seismic characteristics of a series of northwest-southeast trending dykes located in the southern North Sea.

We document the near surface expression of dykes in three-dimensions. Mapping shows that dyke emplacement occurred during the Early Tertiary. Rising volatiles, formed from the interaction between magma and pore-water, have resulted in the formation of sub surface feeder structures and surface collapse pits above the dyke tip. The collapse pits above the dykes have a remarkable resemblance to remote sensing images of Martian pit chain craters. We explore this relationship and its significance to existing theories of pit chain crater formation on Mars. The dykes trace the synclinal axes of regional folds. We investigate the close spatial relationship between dyke emplacement and regional folding and conclude that the dykes have a direct control on folding in the southern North Sea.

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## **Depositionally-limited gravity-driven thrust tectonics from deep water South Africa**

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For at least the past 15 years a new paradigm has developed whereby internal Earth deformation processes are strongly modulated by the action of surface processes. For example, Crustal thickening is limited by the surface topography and so erosion can allow deformation to progress. Similarly, anticline amplification can be dampened by burial under syn-orogenic sediments. Erosion and deposition upon accretionary prisms modifies the taper of the deforming wedge and therefore can influence its dynamical evolution. However, the role of sediment loading and denudation are most keenly experienced by gravitational deformations on continental margins. Tectonics plays little role in these, save in modulating regional slopes. Body forces, supplied by sediment and modified by ongoing deposition and erosion, are the motor. This contribution examines the kinematic evolution of one such system, from the Cretaceous of offshore NW South Africa. Contractional deformation in deep-water is kinematically linked to extension near shore. The whole system is about 175 km wide (about the same as the western Alps). These structures are developed in the early post-rift megasequence of the south Atlantic. The basal detachment dips basinward – indicating that the deformation style is gravity sliding. A profile through this structure, imaged on a 220km seismic line, reveals an array of closely spaced (3-4 km) ocean-vergent thrusts that imbricate about 1500m of stratigraphy. Only a few tens m of growth strata are evident, deposited between thrust anticlines. There is no evidence for erosion and the structures are now buried beneath undeformed slope apron sediments. These relationships from the toe of slope suggest deformation was rapid. However, a different view is obtained from the balancing extensional (or “break-away”) sector on the shelf. This is marked by a complex array of half-graben with oceanward-vergent normal faults. The growth strata indicate incremental faulting and brim-full deposition. Locally over 3 km of growth strata are preserved, reflecting a significant depositional interval (?>1Myr?). Thus contractional deformation was not rapid. The lack of growth strata at the toe of slope reflects the presence of syn-deformational accommodation on the shelf and upper slope. Brim-full syn-deformational deposition indicates that the structures were driven and their bulk strain rate governed by the sedimentation. The study indicates that submarine slope failure, even gravity sliding, need not become catastrophic. It may be interesting to contemplate how these processes combine with plate-coupled deformations to influence the bulk structure and dynamics of thrust systems at destructive plate boundaries.

## Archaeoseismology: a logical approach

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The cultural effects of ancient earthquakes have long been of interest to archaeologists and historians but such archaeological data have remained largely neglected in seismic-hazard studies. Whilst geological data derived from palaeoseismology are now widely integrated into formal assessments for the probability of occurrence and severity of future earthquakes in a given area, archaeoseismic data are not, their reliability tainted by the highly subjective nature of cultural interpretation.

However, many of the uncertainties that plague archaeoseismic studies are also inherent in palaeoseismic studies, where field observations of geological phenomena similarly may satisfy several alternatives. Quantification of uncertainties related to palaeoseismic data in seismic-hazard analysis has been addressed by Atakan *et al.* (2000), who outlined a qualitative method by which the relative reliability of a favoured palaeoseismic interpretation with respect to its alternatives could be described. The Atakan method involves a simple logic-tree formalism applied to the palaeoseismological data-interpretation process. Here, we show that the same simple approach can be adopted by archaeoseismic studies.

The Atakan scheme is adapted to fit with the main stages of interpretation in archaeoseismic investigation, which Guidoboni (1996) expresses as a sequence of questions that underpin a seismic hypothesis, namely: (1) from a geological-geophysical point-of-view is an earthquake a reasonable possibility? (2) does the hypothesis of an earthquake accord with archaeological and historical evidence? (3) has a good stratigraphical check been carried out so that one can be sure that the deformations observed are not due to later seismic events? (4) can human factors or other natural phenomena such as landslips be excluded as the cause of the destruction observed? and (5) is the destruction widespread and can it be correlated with other similar situations over a wide area?

In our archaeoseismic scheme, these questions are recast as consecutive stages of analysis that examines (1) Tectonic setting, (2) Site environment, (3) Site potential, (4) Identification of earthquake damage, (5) Dating of damage, and (6) Extrapolation to other sites. These six interpretative stages conform to nodes on a logic tree at which different alternatives can be described with their associated uncertainties. We adopt the most simple logic-tree approach whereby each node has only two alternatives, one representing the preferred solution and the other the sum of the remaining alternatives. At the end, a joint probability of the preferred alternatives will give a qualitative measure of uncertainty related to the complete archaeoseismic analysis. The final result of this method is the *Archaeoseismological Quality Factor* (AQF), a measure of the confidence attached to the attribution of seismic damage at an archaeological site, and thus an indication of its reliability for inclusion in detailed seismic-hazard analysis.

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## **The systematic treatment of uncertainties in archaeoseismology.**

### **A proof of concept at the ancient city of Sagalassos (SW Turkey).**

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Archaeoseismology aims at using man-made structures as a potential source of palaeoseismological information. This developing discipline is currently at the centre of some controversy, questioning whether or not man-made structures can be used as earthquake indicators at all. While opponents (e.g. Ambraseys 2005, 2006) are focusing on the indiscriminate use of earthquakes as ‘deus ex machina’ in archaeology, supporters (e.g. Kovach & Nur 2006) emphasise the unique opportunity that offer archaeological sites in any attempt to assess the seismic potential of a region.

To overcome the criticism and to ensure the general acceptance of archaeoseismology, a systematic, semi-quantitative and interdisciplinary approach is a prerequisite. We designed a semi-quantitative algorithm, inspired by the logic-tree formalism for palaeoseismology by Atakan (2000), to treat systematically the uncertainties, inherent to the incomplete archaeoseismological record. The final result of this algorithm is the *Archaeoseismological Quality Factor* (AQF), expressing the degree of certainty to which an archaeological site has recorded (a) palaeoearthquake(s) and thus reflecting its relative importance with respect to a seismic-hazard analysis.

As a proof of concept, the algorithm has been successfully tested on the archaeological site of Sagalassos (SW Turkey)(Similox-Tohon et al. 2006). The resulting AQF of 5.3 is a value that could be used directly in a seismic-hazard analysis, although its relative significance can currently not be established because of the lack of other case studies in which the algorithm has been used. When a sufficient number of AQF’s will be produced, a regional comparison will become possible. Moreover, the different stages in the algorithm allows to reveal the weak points in the data set available, enabling to anticipate future investigations to improve the overall AQF of a site (e.g. dating the palaeoearthquakes in the Sagalassos case).

While it has been successfully applied in the Sagalassos case after all evidences has been collected, the algorithm ideally serves as a guide to the excavation director during the investigations at an archaeological site with the prospect of assessing its seismic potential. Eventually, this will lead to an interdisciplinary – truly geoarchaeological – approach, where a proper balance is achieved between archaeologists, historians, geologists, geophysicists and engineers.

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## **Geometry and deformation mechanisms of normal faults in the Nukhul half-graben, Suez rift, Egypt**

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The Nukhul half-graben is an Oligo-Miocene rift basin containing spectacular exposures of the rift-initiation Abu Zenima (continental fluvial and lacustrine) and Nukhul (tidally influenced shallow marine) formations. It is bounded to the northeast by the northwest-striking Nukhul fault and to the south by the east-striking Baba-Markha fault. The Nukhul fault has a maximum displacement of approximately 1 km where it intersects the Baba Markha fault to the south. Displacement decreases northwards to a well-defined fault tip over approximately 11 km. The Baba Markha fault is a major block-bounding structure with displacement estimated at 3.5 km. There are two identifiable fault sets that cut the Nukhul half-graben. The main set strikes approximately northwest-southeast (parallel to the main rift-bounding normal fault zones) while a subordinate set strikes approximately east-west. Our observations of fault and fold geometries, and thickness and facies distributions of stratigraphic units within the syn-rift succession, show that both fault sets were active during deposition of the Abu Zenima and Nukhul formations. Cross-cutting relationships show that the Baba-Markha fault continued to be active after the cessation of activity on the Nukhul fault.

The pattern of fault evolution during syn-rift deposition described above suggests that faults are active while processes of compaction and diagenesis in the accumulating sediment pile are ongoing. This leads to the expectation that the deformation mechanisms active within the fault zones will have evolved through time as the mechanical properties of the deforming material changed. In this study we use field observations of mesoscale fault geometry and architecture, coupled with digital outcrop mapping of fault systems at the macro-scale, to examine the evolution of fault geometry and deformation mechanisms through time.

## Folding attached to hangingwall cut-offs of normal faults

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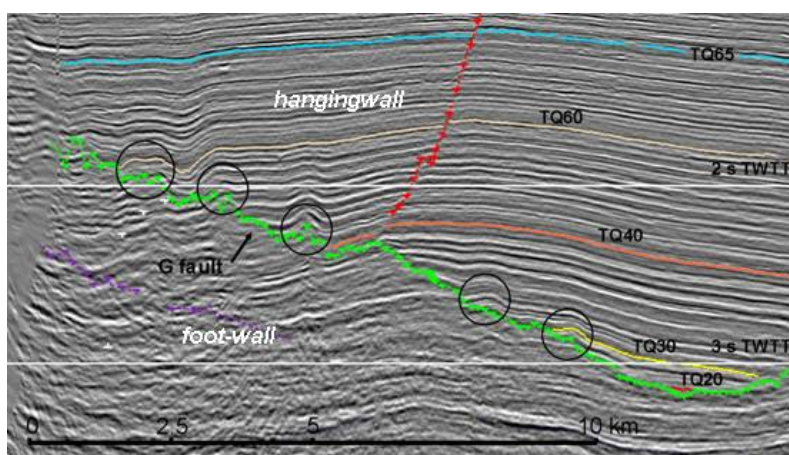
A series of small anticlines attached to the hangingwall cut-offs of normal faults are described from both seismic (Columbus Basin, off-shore Trinidad) and field examples (Kilve, Somerset). They have also been seen in several published interpretations of fault zones, where they may be accompanied by broader hangingwall synclines. They differ from more usual irregularities in hangingwall basins (e.g. Anders and Schlische 1994) by being attached to the fault cut-off. Similar features can be recognised in active extensional faults (notably in the Basin and Range), where they are associated with variation in co-seismic slip along faults.

The anticlines occur at regular intervals along the fault and appear to develop independently of the geometry of the footwall cut-offs. They are often associated with subtle corrugations or steps in the fault surface and are interpreted in terms of fault segmentation. The effect of these hangingwall anticlines is to produce a series of throw minima along the fault (e.g. Peacock and Sanderson 1996), but they can be distinguished from other forms of relay ramp structures by their characteristic geometry on diagrams of foot-wall and hangingwall cut-off diagrams. The throw variations and undulations of the hangingwall cut-offs may be preserved despite accumulation of large subsequent displacements, and examples of this from the Columbus Basin will be discussed.



Example of anticlines attached to hangingwall cut-offs, Kilve, Somerset, UK

Example of hangingwall anticlines in section sub-parallel to a fault in the Columbus Basin, Trinidad.



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## **Brittle fault pattern along the Campbell Fault, a major right-lateral strike-slip fault system in northern Victoria Land, Antarctica**

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In the last decade, an increasing body of evidence has been collected in northern Victoria Land, supporting the occurrence in this region of the Antarctic plate of a network of NW-SE oriented, Cenozoic right-lateral strike-slip fault systems (Salvini et al., 1997; Rossetti et al., 2003). Specific expeditions were carried out to collect structural data along the Priestley Fault (Storti et al., 2001) and the Lanterman Fault (Rossetti et al., 2002). The presence of other six major fault systems has been mostly inferred from offshore seismic reflection profiles and onshore morphotectonic evidence (Salvini et al., 1997; Salvini and Storti, 1999).

In this contribution, we report on new structural data collected along the Campbell Fault, located along the homonymous glacier. The fault system mainly cuts across granitic rocks, with minor metamorphic relics. Despite the principal displacement zone of this fault system is inferred to lie below the glacier, subsidiary fault data in the damage zones allowed us to constrain the kinematics of this major brittle shear zone. Many subsidiary faults have narrow cores of cataclastic rocks, sometimes including pseudotachylytes. Shear sense criteria were provided by grooves, corrugations, and by subsidiary faults and fractures associated to the master slip surfaces and, in few cases, by quartz shear fibres on slickensides. Structural data analysis indicates for this fault system a right-lateral strike-slip sense of shear, supporting previous inferences. Our data provide further support to the role of major right-lateral strike-slip fault systems in determining the Cenozoic tectonic picture of Victoria Land and the Ross Sea.

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## Physical modelling of basement controlled normal faulting in wedge-shaped cover sequences

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Basement controlled normal faulting has been studied extensively in the past using a variety of approaches, such as physical (sand, clay), numerical (FEM) and analytical modelling. Typical boundary conditions include a rigid basement, containing pre-cut faults, which is overlain by a (brittle) cover. The base cover interface is typically horizontal and the (sand, clay) model is extended under plane strain conditions. Under these simple boundary conditions the growth pattern – details of which depend on the dip of the basement fault and the rheology of the overburden - within the cover sequence can be summarized as follows: (i) A steep precursory fault develops, which is often convex up and is therefore a reverse fault close to the top of the surface of the cover. (ii) A shallower dipping masterfault later develops in the footwall of the precursory fault. (iii) If the masterfault within the cover has a steeper dip than the pre-cut fault, antithetic adjustment faults develop. In summary, faults that develop under these boundary conditions often comprise multiple slip surfaces, partly due to free surface effects and fault refraction, i.e. fault dip variations between pre-cut and cover fault. Systematic stepping of fault segments is not expected under these boundary conditions. In this talk we show that systematic and predictable stepping a fault segments above a pure dip slip normal fault can be generated in the cover using an inclined base cover interface.

We have performed a series of sandbox experiments in order to investigate the impact of a dipping base cover interface on fault growth and geometry. Normal faults developing in the analogue material have fault dips of ca 65°. We varied both the dip of the basement faults and the dip of the base cover interface: the basement faults have dips of 45 and 70° and the base cover interface has dips of 0, 10 and 20° and its strike was always normal to the strike of the pre-cut faults. Using the stereonet it can be easily shown that under boundary conditions where the base cover interface is inclined, strike changes of the faults within the cover are expected, if the fault dip within the cover is not exactly the same as the pre-cut fault dip. This is due to the fact that a continuous fault that refracts across the interface has to have the same fault/interface intersection lineation. An alternative outcome is, however, that the cover faults are comprised of dip-slip fault segments that exhibit systematic stepping.

Our simple geometrical predictions of the orientation of cover faults are verified with our sandbox experiments. In addition to the typical growth sequence of basement controlled normal faults described above we observed either fault strike changes or systematic stepping of fault segments within wedge-shaped sand covers. The frequency of relays that develop between the overlapping segments increases with increasing dip of the base cover interface. Our results highlight the fact that systematic stepping of faults above a basement fault is not necessarily a kinematic indicator of oblique-slip reactivation and we advise caution regarding interpretation of fault kinematics from stepping directions alone. Our model also suggests that refracting normal faults in inclined multilayers will most likely be segmented.

## **Abstracts: Poster presentations (alphabetical order)**

## **Correlation of organic and inorganic thermal indicators in the Apenninic-Maghrebian fold-and-thrust belt: a case study from Eastern Sicily**

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Temperature dependent clay mineral assemblages and vitrinite reflectance data have been used to investigate levels of diagenesis from the Apenninic-Maghrebian fold-and-thrust belt in Eastern Sicily at the footwall of the Peloritani-Calabride Arc. Data are from chain units sampled along a regional transect between the Nebrodi Mountains to the North and Mt. Judica to the South. These units developed in very different tectonic settings from oceanic to passive continental margin domains deformed during the Cenozoic chain building- and related active margin deposits.

The integration of organic and inorganic thermal indicators allowed us to distinguish among different tectonic settings with thermal maturity generally decreasing from hinterland to foreland as a result of progressively less severe thermal evolution and/or tectonic loading during the chain building. Specifically, highest VR<sub>o</sub>% values (ca. 0.60-0.75%) and percentages of illite in I-S (60-80%) are found in trench-involved and in accreted passive margin units. Lower VR<sub>o</sub>% values (0.20-0.47%), and illite percentage in I-S (30-60%) are found in thrust-top and foredeep basin deposits and far-travelled Sicilide Units that have escaped involvement in trench evolution. Furthermore, either sedimentary or long-lived tectonic burial (at least more than 5 My) seem to have affected levels of diagenesis of the studied successions.

The correlation between organic and inorganic thermal indicators is satisfactory for most of the samples derived from hemi-pelagic and siliciclastic deposits, whereas it is poor for some proximal siliciclastics. A tentative calculation of paleo-temperatures is also proposed for the studied tectono-stratigraphic units.

## **Unravelling the sedimentary and tectonic burial history of the Laga Basin (Central Apennines, Italy): constraints from combined organic matter and clay mineral data**

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In the external zone of fold-and-thrust belts, where levels of thermal evolution are generally low, it gets difficult to discriminate between the contribution to thermal maturity due to either tectonic or sedimentary burial. This is particularly true for sedimentary sequences deposited in basins characterized by highly variable subsidence rates such as syn-orogenic basins. Quantifying the amounts of thermal maturity due to different causes may be particularly significant for hydrocarbon exploration.

In the present study, the combined use of different thermal indicators in diagenesis (vitrinite reflectance, Tmax and percentage of illite in illite/smectite mixed-layers and chlorite in chlorite/smectite mixed-layers) allowed the reconstruction of thermal maturity patterns in the external zone of the central Apennines, in the Messinian Laga Basin. It is located to the East of the Sibillini Mts. and to the North of the Gran Sasso Range, that represent two of the main Meso-Cenozoic carbonate backbones of the Central Apennines. Since Lower Messinian this basin acquired the typical feature of a foreland basin and the siliciclastics of the Laga Fm. filled it up. We focused sampling on the lower and middle siliciclastic members of the Laga Fm. developed to the west of the Montagna dei Fiori-Montagnone alignment where facies architecture, subsidence amounts, and tectonic loadings (now eroded) show a considerable variability along both strike and dip of the chain. Subordinately pre-orogenic succession was sampled in the structural culminations surrounding the basin (e.g., Montagna dei Fiori area).

About 45 samples for vitrinite reflectance analysis and XRD analysis of the <2µm grain size fraction were mainly collected from surface outcrops. These data were integrated with Tmax data derived from 75 surface and subsurface samples (outcropping Gorzano Mt. section and Varoni 1 well).

Our major results include:

- (i) the documentation of a general trend of decreasing thermal maturity in the pre-evaporitic member from the Sibillini front to the Montagna dei Fiori-Montagnone alignment. Data range from early mature to immature when compared to stages of hydrocarbon generation;
- (ii) a direct correlation of thermal maturity data with subsidence amounts;
- (iii) a local influence of the tectonic emplacement of the Sibillini Mts. and Gran Sasso Range structures onto the Laga Basin;
- (iv) a low thermal maturity of the analysed pre-orogenic Meso-Cenozoic succession of the Montagna dei Fiori;
- (v) a tentative correlation among different thermal indicators in diagenesis.

## Multi-scale sheath folds in salt, sediments and shear zones

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Sheath folds are developed in a broad spectrum of geological environments in which material flow occurs, including gravity-driven surficial deformation in ignimbrites, unconsolidated sediments and salt, together with deeper level ductile shear zones in metamorphic rocks. This study represents the first geometric comparison of sheath folds in these different settings across a wide range of scales. Elliptical closures defining eye-folds represent (y-z) cross sections through highly-curvilinear sheath folds. Our analysis of the published literature, coupled with field observations, reveals remarkably similar ellipticities ( $R_{yz}$ ) for sheath folds in metamorphic shear zones ( $R_{yz}4.23$ ), salt ( $R_{yz}4.29$ ), sediment slumps ( $R_{yz}4.34$ ), glacioteconites ( $R_{yz}4.48$ ), and ignimbrites ( $R_{yz}4.34$ ). Nested eye-folds across this range of materials ( $N=1800$ ) reveal distinct and consistent differences in ellipticity from the outer- ( $R_{yz}$ ) to the inner-most ( $R_{y'z'}$ ) elliptical “rings” of individual sheath folds. The variation in ratios from outer to inner rings ( $R' = R_{yz}/R_{y'z'}$ ) in gravity-driven surficial flows typically displays a relative increase in ellipticity to define cats-eye-folds ( $R' < 1$ ) similar to those observed during simple and general shear in metamorphic rocks. We show that sheath folds develop across a range of scales within these different environments, and display elliptical ratios ( $R_{yz}$ ) that are remarkably constant ( $R^2 > 0.9$ ) across 9 orders of magnitude (sheath y axes range from  $\sim 0.1\text{mm}$  to  $> 75\text{km}$ ). Our findings lead us to conclude that the geometric properties of sheath folds are primarily controlled by the type and amount of strain, with  $R'$  also reflecting the rheological significance of layering associated with original buckle fold mechanisms. The layering and banding that defines sheath folds may thus be rheologically significant during the generation of pre-cursor buckle folds across a broad range of materials and environments. With continued deformation, the layering marking the original folds may become increasingly passive to define sheath folds. These empirical relationships suggest fundamental and universal constraints on sheath folding across a broad spectrum of materials, strain rates and scales encompassing a variety of deformation settings.

## Testing plate reconstructions for the high Arctic using crustal thickness mapping from gravity inversion

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The plate tectonic history of the Amerasia Basin (High Arctic) and its distribution of oceanic and continental lithosphere is poorly known. A new method of gravity inversion with an embedded lithosphere thermal gravity anomaly correction has been applied to the NGA (U) Arctic Gravity Project data to predict crustal thickness and to test different plate reconstructions within the Arctic region. Two end member plate reconstruction models have been tested: in one model the Mendeleev Ridge is rifted from the Canadian margin while in the other it is rifted from the Lomonosov Ridge. The inversion of gravity data to map crustal thickness variation within oceanic and rifted continental margin lithosphere requires the incorporation of a lithosphere thermal gravity anomaly correction for both oceanic and continental lithosphere. Oceanic lithosphere and stretched continental margin lithosphere produce a large negative residual thermal gravity anomaly (up to -380 mGal), for which a correction must be made in order to determine realistic Moho depth by gravity anomaly inversion. The lithosphere thermal model used to predict the lithosphere thermal gravity anomaly correction may be conditioned using plate reconstruction models to provide the age and location of oceanic lithosphere. Two end-member plate reconstruction models have been constructed for the opening of the Amerasia Basin and used to determine lithosphere thermal gravity anomaly corrections: in one model the (presumably) continental Mendeleev Ridge is rifted from the Canadian margin in the Jurassic while in the other it is rifted off the Lomonosov Ridge (Eurasia Basin) in the Late-Cretaceous. Crustal thickness predicted by gravity anomaly inversion for the two plate reconstructions is significantly different in the Makarov Basin because of their different lithosphere thermal gravity corrections. The plate reconstruction with younger Makarov Basin ages gives a crustal thickness of the order 6-8 km thinner than the older Makarov Basin model. A crustal thickness of approximately 20 km has been obtained from seismic refraction data (Lebedeva-Ivanova et al., 2006) which would imply a Late Mid-Cretaceous age for the Makarov Basin. In this case plume-related forces may have contributed to the opening of this basin, as regional plate tectonics predict compression and not extension in the Makarov Basin area at this time.

## **Development of lattice preferred orientation in clino-amphiboles deformed under low-pressure metamorphic conditions: SEM/EBSD study of metabasites from the Aracena metamorphic belt (SW Spain)**

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The mechanical properties of the lower continental crust are intimately related to the rheology of calcic clino-amphibole. Naturally deformed clino-amphibole typically shows brittle behaviour under a wide range of deformation conditions, whereas crystal plasticity is rarely observed. In this study, the SEM-EBSD determined petrofabrics of clino-amphiboles from metabasites of the Aracena metamorphic belt (SW Spain), deformed under low-pressure/medium-to-high temperature metamorphic conditions, are presented. Amphiboles from all samples have developed LPO that can be attributed to different deformation mechanisms depending on deformation temperature, fluid content, structure and phase-strength contrasts. Rigid body rotation of amphibole prisms within a weaker plagioclase matrix corresponds to metabasites deformed under medium deformation temperatures that show a weak layer structure and a high phase strength-contrast between plagioclase and clino-amphibole. Lower temperatures and the presence of fluids mean that one of the studied rocks was affected also by dissolution-precipitation creep and cataclastic flow. In the final sample, dislocation creep was accommodated by recovery and subgrain rotation dynamic recrystallisation in monomineralic hornblende layers at higher temperatures, which could be representative of the rheology of amphiboles in the lower continental crust.



## **Subduction thrust fault characteristics at different scales and depths – examples from an exhumed plate boundary zone**

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Subduction thrust faults at convergent plate margins are the most seismically active areas on earth. Due to the inaccessibility of recently active subduction zones for direct investigations, the study of fossil examples, especially in the Central Alps, is the most promising approach to understand subduction zone processes and thrust fault zone characteristics.

For this purpose we studied a fossil plate boundary zone within the Central Alps of Europe. The formerly south to southeast dipping zone is sandwiched between the overlying Austroalpine nappes (African plate) and the Penninic/Helvetic nappes (European plate), a setting assembled during Alpine convergent plate motion. We investigated the fossil thrust fault system at various scales ranging between geological maps, outcrops and investigations of thin sections using polarization microscope and SEM. On the largest scale, we compare the distribution of recent aftershock data, as well as the  $V_p/V_s$  ratios, and reflectivity data obtained along active convergent plate margins with their possible ancient counterparts. Due to large scale tilting of the fossil plate boundary zone, a coherent outcrop allows the exploration of the thrust fault system at various depths. The subduction thrust system consists of a *mélange* zone with a shaly matrix. Individual layers of sandstone or more pristine carbonates are affected by extensional cracking in the shallow parts of the fossil plate boundary zone. With increasing deformation and metamorphism these layers start to boudinage, and later on they form separated clasts with increasing aspect ratio. Other clasts are derived from the upper plate basement and metasediments as well as slivers of the oceanic lower plate and its sedimentary cover. Towards depth they are strongly mylonitized along the rims, and mylonitic shear zones cut into them to enforce disintegration. The shallow portions of the subduction thrust zone are characterized by zones of localized deformation, which are getting broader and subsequently turn into a distributed deformation with increasing depth. The prominent deformation mechanism within the shallow parts of the fossil subduction thrust zone is pressure solution in carbonatic rocks, which includes the formation of stylolites. Towards formerly deeper subducted parts intracrystalline deformation of quartz starts to dominate. Pseudotachylytes as evidence for unstable slip have been found at a limited depth range (app. 3-6 kbar, <350°C) at the base of the upper plate within a zone of some 100 m width. Mutual crosscutting of pseudotachylyte veins with mylonitic shearzones is visible both at macroscopic and microscopic scale. Deeper along the exhumed plate boundary zone, metasedimentary clasts and metabasics reveal abundant hydraulic fractures with partly blocky mineralization. Additionally, a vast number of foliation-parallel mineralized veins invade the matrix of the fossil subduction thrust system. The relationship of these mineralized fractures to seismic faulting has yet to be evaluated. They mirror dehydration processes during prograde metamorphism within the subduction zone. Rb/Sr isotope signature of 8 lower plate carbonatic samples provide clear indications for the presence of fluids with elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios circulating through the subduction thrust system, suggesting that dehydration of continent-derived sediments was the main fluid source.

## **Human bias in geological interpretation – how much uncertainty does it introduce?**

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To quantify the range in interpretations of geological data by professionals, we have asked over 200 geoscientists to interpret a seismic section. Our aim was to assess the impact of interpretation on structural models and, ultimately, on prospectivity. A crucial element of the project was to create a known geological scenario, to compare interpretations against, a 'catch 22' situation if using 'real' seismic. We have created our data-set in the structural modelling and restoration program 2DMove in which we determined the input parameters for the model. Synthetic seismic was 'shot' across the model to create an image for interpretation. Individuals were asked to interpret the image and provide information on their level of experience in: years, tectonic regimes, industry, academia etc.

Initial findings suggest that people's previous experience affects both their approach and the outcome of their interpretation. Differing interpretational styles have resulted in interpretations of the single data-set ranging from salt to inversion tectonics. We have quantified the range in interpretation of the seismic data set for style and tectonic regime, and consider the impact this has on potential prospectivity. Our initial results show that those that have worked predominantly in a particular tectonic regime have in many cases brought their experience from that regime to play in their interpretation. Their prior knowledge has biased their interpretation. Can we quantify the bias of individuals in the generation of this range of interpretations and modify industry workflows to minimise the impact on prospectivity?

## Neogene tectonic evolution of the Hatay Graben, south central Turkey.

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New structural and sedimentary studies form the basis of a new interpretation for the Neogene Hatay Graben. Fault analysis reveals three contemporaneous trends of fault orientation (000°–180°, 045°–225° and 150°–350°) suggesting that the graben is transtensional in nature. Sedimentary studies show that, following shallow-marine deposition from the Late Cretaceous to the Eocene, a hiatus ensued until Early Miocene fluvial sedimentation. After a Mid-Miocene marine transgression, water depths increased until the Messinian salinity crisis, followed by a regression from the Pliocene to the present day. The basin initially developed as the distal margin of a foreland basin of the Tauride allochthon to the north, developing a classic sedimentary sequence during Mid–Late Miocene. Stresses caused by loading of the crust created a flexural forebulge to the south that supplied sediment mainly northwards. During the Plio-Quaternary, transtensional graben development took place, primarily influenced by the westward tectonic escape of Anatolia along the East Anatolia Fault Zone and left-lateral offset along the northward extension of the Dead Sea Transform Fault. This area is, thus, an excellent example of a foreland basin reactivated in a strike-slip setting. Our new data are used to support a two-stage model for the development of the Hatay Graben. During the Miocene, the area was part of a flexural foreland basin of the Arabian plate, associated with active normal faulting. The Late Miocene (Messinian) was characterised by a transition from a collisional tectonic regime to a transtensional one, during which fault localisation took place. The neotectonic Hatay Graben then developed during the Plio-Quaternary following a switch from regional convergence to left-lateral strike-slip and "tectonic escape". We infer that the graben is currently undergoing transtension, and that strain partitioning has lead to the graben flanks being dominated by normal faults and the graben axis by strike-slip faults. The large faults may merge at depth into a major strike-slip zone that forms part of the diffuse Africa-Anatolia plate boundary in this region.

## **Structural inheritance during positive tectonic inversion: an example from the Lagonegro units of central Lucania, Italy**

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The Lucanian Apennines of Southern Italy are an arcuate fold-and-thrust belt developed as a result of imbrication of different tectonic units, namely the Ligurian, Apenninic and Lagonegro Units, onto the Apulian Foreland. These tectonic units, differentiated since Triassic time, were originated in distinct palaeogeographical domains that are, from west to east: the Ligurian Basin, the Apenninic Carbonate Platform, the Lagonegro Basin and the Apulian Platform. Differentiation of the palaeogeographical domains was controlled by syn-sedimentary, pre-orogenic normal faults developed during the rifting stage that led to the Mesozoic Neotethys Ocean and to drifting of the African (i.e. Adria) and European continental margins. From Eocene time onwards the palaeogeographical domains experienced contraction related to the closure of the Neotethys Ocean and to the contraction of the Adria continental margin, with development and imbrication of the main tectonic units. Mesozoic, pre-orogenic normal faults were overprinted by Tertiary thrusts and related folds during this episode of positive tectonic inversion. A wide literature has long suggested that the contractional geometry and kinematic evolution of the Lagonegro Units were largely controlled by Mesozoic, pre-orogenic normal faults; however, these faults have mainly been inferred from the stratigraphic variations of syn-rift Mesozoic sediments across them. Indeed, surprisingly little documentation has been provided so far, though with rare exceptions, to constrain the local attitude and kinematics of pre-orogenic extensional structures within the Lagonegro Units. The results of recent research carried out in Val d'Agri, in the central part of the Lucanian Apennines, made it possible to recognise a macroscopic, pre-orogenic normal fault, whose occurrence within the template effectively controlled the geometry and kinematic evolution of the subsequent contractional structures. It appears significant to emphasize that this history of structural inheritance during positive tectonic inversion did not involve reverse fault reactivation, as it has been assumed for this part of the Lucanian Apennines.

## **Pips, flakes, exhumation of UHP rocks and Alpine orogenesis; a tectono-geochronological perspective.**

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Geochronological data are now commonly used to establish the timing and rates of exhumation of high pressure metamorphic rocks, critical for testing geodynamic models of orogenic belts. Such approaches must be used with care. Ages of peak high pressure metamorphic assemblages allied to younger cooling ages give a general insight into the rates of exhumation when tied to PT paths. However, the results of this workflow are difficult to relate to the kinematic history and therefore maybe of limited use in the critical testing of exhumation models. A better alternative is to date directly the synkinematic mineral phases in characterised deformation zones. This point is illustrated by examples drawn from the deformed and variably subducted “European” continental crust now exposed in the Western European Alps. Greenschist facies shear zones, with synkinematically recrystallized mica dated using the Rb-Sr system, were active synchronously for c. 100km along strike (e.g. the regional “retrocharriage” shear system of the Eastern Briançonnais at 34 Ma). However, UHP terrains preserved in the basement massifs attained peak pressures and were exhumed diachronously (38 Ma - 32 Ma). These results indicate that tectono-metamorphic histories based on single orogenic transects may give misleading pictures of geodynamic evolution. In an Alpine context it appears that exhumation of UHP and shallower parts of the evolving continental subduction channel occurred as variably detached flakes rather than relate to the dynamics of larger scale plate processes. In this model, the propensity for subducted continental crust to return to conventional depths in the lithosphere is controlled by two distinct parameters: the density of the subducted crust (and hence the composition of its eclogites); and the shear strength of potential failure zones along which the exhuming crust detaches from the underlying, dense lithosphere (e.g. the Moho). There is no a priori reason why weakening and detachment formation should be synchronous along orogenic systems. Thus the buoyant return of subducted crust, its coupling into external thrust systems and their kinematics can generate complex 3D structures, as illustrated in arcuate Alpine orogens.

## What controls fault activity and earthquake recurrence?

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Current models for earthquake recurrence and seismic hazard are based on the key principle that there exists a mean recurrence interval,  $T_{mean}$ . For areas of active crustal deformation where there is a large number of active faults, and/or the regional strain rate is relatively low, historical earthquake catalogues are unable to provide adequate constraints on  $T_{mean}$  because the earthquake cycle of some faults is longer than the catalogue itself. Current practice in seismic hazard analysis is to characterise variability in recurrence interval by defining the Coefficient of Variation (CV) for a sequence of earthquakes where  $CV = \sigma / T_{mean}$ , and  $\sigma$  is the standard deviation of the inter-event times. A perfectly periodic sequence of earthquakes would yield  $CV = 0$ . In reality CV values for earthquake recurrence intervals are poorly constrained (ranging from 0.2 to 0.7) yet small differences in CV can lead to order of magnitude difference in conditional probability calculations for future seismic shaking. Numerical models that include elastic interaction between active faults predict that there should be a systematic variation in rupture history on faults depending on their position and orientation relative to neighbouring structures and the overall regional tectonic loading. This theoretical prediction has the potential to change significantly the way we understand and ultimately predict patterns of earthquake recurrence. We aim to test this prediction in an area of active normal faulting in the central Apennines of Italy where we are able to exploit the widespread occurrence of well-preserved bedrock scarps formed since 12-18ka that are amenable to  $^{36}\text{Cl}$  cosmogenic surface exposure age determination. We aim to use LiDAR to map the bedrock scarps in order to identify the best sites for sampling. The cosmogenic exposure age profiles will allow us to reconstruct the detailed slip history on individual faults over multiple earthquake cycles. We aim to derive slip histories on faults with differing structural geometries and to compare these data to output from a numerical model for elastic interaction between faults.

## **Alpine tectonic exhumation of the Aspromonte Unit, Calabrian Arc, Italy**

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In the Calabrian Arc (southern Italy), the Stilo and Aspromonte Unit represent the topmost nappes of the mountain belt. The Stilo Unit, in the hanging-wall, include both Variscan basement and Mesozoic sedimentary cover rocks, recording no Alpine metamorphism. The footwall Aspromonte Unit consists of amphibolite-facies Variscan basement rocks showing localised Alpine metamorphic overprint: an early one occurred at  $T = 500 \pm 30^\circ \text{C}$  and  $P = 5 \pm 1 \text{ kbar}$ ; the second stage occurred at lower-pressure and similar or higher temperature conditions, and it is accompanied by intense deformation. The timing of exhumation of the Aspromonte Unit is constrained by fission track analysis carried out on both zircon and apatite. Available data indicate significant cooling and exhumation of the study crystalline basement rocks between  $\sim 35$  and  $\sim 15 \text{ Ma}$ . The fact that the rocks of the Aspromonte Unit – affected by Alpine metamorphism reaching  $T$  around  $500^\circ \text{C}$  – are presently overlying units showing little or no Alpine metamorphic overprint, indicates that substantial exhumation had occurred prior to the final emplacement of the Aspromonte Unit onto the underlying rocks. The aim of the present work is to discuss the evidence for extension-controlled exhumation of the Aspromonte Unit. Detailed geological mapping and structural analysis in NE Sicily and S Calabria point out the occurrence of extensional structures of different types. These include high- and low-angle faults and shear zones. Greenschist-facies mineral assemblages from such shear zones record extensional deformation occurring at depth, most probably during (and probably controlling) exhumation of the study rocks. Ductile shear zones range from a few cm thick mylonite and ultramylonite horizons, showing sharp boundaries with the wall rock, to tens of cm thick foliated levels characterised by extensive development of S-C-C' fabrics. Extensional/oblique-slip shear zones and faults show variable attitudes. However, the pattern of associated lineations shows a clearer kinematic pattern, dominated by top-to-the-NNW and top-to-the-SSE extensional shear. Kinematic analysis carried out on the main tectonic contact between the Stilo and Aspromonte Units in southern Calabria point out a consistent a top-to-the-NNW sense of shear. Based on the general vergence of Calabrian Arc nappes, and on the 'normal-sense' pressure break occurring between the Stilo and Aspromonte Units, the tectonic contact between the Stilo and Aspromonte Units -best interpreted as being of extensional type- is likely to have controlled syn-convergence exhumation of the Aspromonte Unit.

## **Does X-ray pole figure goniometry always reflect the preferred orientation of paramagnetic carriers in low-grade pelites?**

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The anisotropy of magnetic susceptibility (AMS) is a commonly used petrofabric tool that is applied in many geological environments for quite a number of purposes (determination of palaeocurrent, magma flow, tectonic transport,...). However, within a given rock, AMS is controlled by all magnetic carriers present (*s.l.*; diamagnetic, paramagnetic or ferromagnetic; in fact every material above 0 Kelvin). Consequently, generally AMS cannot be interpreted in terms of geological processes, unless all the magnetic (*s.l.*) carriers and the different magnetic orientation populations are identified. In cleaved, low-grade metapelites, in which, judging from the bulk susceptibility and the degree of anisotropy, paramagnetic carriers control AMS, one often uses X-ray pole figure goniometry (X-PFG) to determine the preferred orientation of the paramagnetic carriers. Indeed, within metapelites, clay minerals are the main paramagnetic carriers, which, together with quartz (diamagnetic carrier), represent the bulk of the rock. Possible mismatches between X-PFG- and AMS-results can often be attributed to traces of ferromagnetic carriers (*e.g.* magnetite).

We applied X-PFG and AMS on the Lower Palaeozoic metapelites of the Anglo-Brabant Deformation Belt (Belgium). In addition, also the preferred orientation of the ferromagnetic carriers was determined using the anisotropy of the anhysteretic remanent magnetisation (AARM). For the Cambrian deposits, AMS can be resolved by means of X-PFG and AARM. For the Silurian deposits, however, in which AMS is controlled by paramagnetic carriers, a mismatch occurs between the results of AMS, X-PFG and AARM. In these pelites, the preferred orientation of chlorite and white mica (X-PFG) is always subparallel to cleavage and also the AARM is generally parallel to cleavage (~70%). However, the AMS foliation is subparallel to cleavage in only ~45% of the samples, the remainder being parallel to bedding (~15%) or having an intermediate orientation (~40%). This suggests the presence of a bedding-parallel paramagnetic carrier that partly controls AMS, but is not detected by X-PFG. In order to check this hypothesis, AMS was performed at ~77K (liquid nitrogen), which enhances the paramagnetic signal. In addition, for a few samples also a torque magnetometer was used. These results show that, although X-PFG suggests a cleavage-parallel paramagnetic phyllosilicate fabric, in both the Silurian and Cambrian samples the paramagnetic AMS (low-T-AMS) is subparallel to bedding.

The results imply that, even in metapelites in which the phyllosilicates are considered to represent the main paramagnetic carriers, X-PFG will not necessarily provide the paramagnetic carrier orientation. Any attempt to link AMS to strain in metapelites, hereby using X-PFG, is therefore quite questionable.



## **Complex folding and possible tectonic block rotation in a transpressional restraining bend along the Archaean Carajas strike-slip system, Amazon Craton, Brazil**

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The Carajás Fault Zone (CFZ) is the most prominent structure in the E-W-trending Carajás Strike-Slip System (CaSSS), an ancient upper crustal fault network of probable Late Archaean age that cuts across the basement gneisses of the Precambrian Amazonian Craton in Brazil. The subvertical faults display a complex, long-lived history of movement (>1 Ga) dominated by oblique- and strike-slip displacements. A postulated early regional phase of dextral movement downfaulted units of low-grade to unmetamorphosed cover rocks into dilational bends and offsets in the CaSSS. Subsequent sinistral transpression ca 2.6 Ga led to faulting and folding during partial inversion of the cover rocks in these dilational sites with much of the associated deformation focused in the immediate vicinity (< 2 km) of the major fault traces.

The Carajas North Ridge located in the northern part of the Carajás Region is predominately underlain by cover sequence Archaean volcano-sedimentary rocks of the Grao Para Group. The rocks mainly comprise an intercalated and folded sequence of basic volcanics, banded iron formations, and ironstones. A regional scale study of satellite images linked to outcrop scale detailed structural mapping has led to the recognition of folds on a number of scales. The distribution of folding is highly heterogeneous, with cm- to m-scale structures characteristically related to steeply dipping NW- to NNW-trending zones of folding ('deformed zones'). Fold styles at this scale vary from kink bands and chevron folds showing monoclinic or triclinic patterns through to open to isoclinal parallel folds. Some of this variation may be controlled by variations in lithology/rheology, but it appears also to reflect highly heterogeneous strain. The axial plane orientations are variable with predominantly NW-SE and E-W trends and moderate to steep dips to the NE or N. Fold axes orientations are also variable with a clear predominance of shallow to steep NW plunges. On a regional scale, the shape of the N4 and N5 ironstone outcrops in map view illustrates the presence of kilometre-scale major folds. The shape of the N4E Mine outcrop, for example, suggests a NE verging kilometre-scale antiform-synform pair with a beta axis plunging 45° NW. Regionally, the folds verge in three distinct directions: NE, SW, and subordinately to NW. The patterns are in some ways reminiscent of a classical 'flower structure'.

A lineament analysis from the remote sensing images reveals a set of NW- to NNW-trending lineaments trending upwards from the main trace of the Carajás Fault. Field mapping suggests that these lineaments correspond to the 'deformed zones' of cm- to m-scale folding. We propose a model in which the kilometre-scale folds and the 'deformed zones' formed in a restraining bend during sinistral movements along the sinistral CaSSS. It is suggested that the 'deformed zones' bound a series of clockwise rotating blocks that partially reoriented many of the early-formed transpressional folds leading to a complex and heterogeneous folding pattern. Similar features are likely to occur in other folded zones located in strike-slip restraining bends worldwide.

## **The rheological behaviour of deformed clastic rocks, as exemplified by the conglomeratic gneiss of the Lebendun Nappe, Ticino, Switzerland.**

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The Lebendun Nappe is situated adjacent to the frontal part of the Maggia nappe within the Lower Penninic zone of the Lepontine Alps, and exposes a spectacularly deformed conglomerate. The conglomerate has been subjected to four stages of deformation, identified on the basis of overprinting criteria of micro and macro structures, and hence is inferred to have been deformed over a variety of pressure/temperature conditions.

From field studies of the conglomeratic gneiss the embedded clasts can be subdivided into four main groups; aplites, quartzites, metagranitoids and mica schists. Using the  $R_f/\phi$  strain analysis technique, it was found that the more strain is progressively accommodated within the more micaceous rocks. Thus the ductility contrast of each group of pebbles with the matrix is a function of its composition. Strains in clasts of different lithologies can be interpreted in terms of the different rheological behaviours of each rock type under given pressure/temperature conditions.

Fry analysis of the deformed pebbles showed that there is in broad terms substantial variability in the K values, ranging from the near-flattening field through to a purely constrictional deformation. This variability may be related in part to regions of higher and lower strains in the limbs of a major  $F_2$  antiform or alternatively related to the overprinting of strains in an  $F_4$  regional backfold of the frontal part of the Maggia nappe.

There is also a degree of variability in K values between different clast types, even in the same exposure. The more mica-poor clasts tend to display more nearly plane strain shapes, whereas in addition to being systematically more highly strained, the more micaceous clasts tend to show more constrictional deformations. It is not clear how these latter differences arise.

In the further development of this study synthetic specimens of clastic rocks are being prepared for high pressure/temperature experimental deformation studies. Specimens are being prepared not only with a known mechanical contrast between (spherical) clasts and a weaker matrix, but also with a range of different clast types embedded within the same specimen. This will aid understanding of the behaviour of naturally deformed polygenetic clastic rocks such as those studied in the Lebendun nappe.

## **Structural control on gas hydrates dissociation and fluid flow migration in the Upper Miocene sediments of the Tertiary Piedmont Basin (NW-Italy).**

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The Messinian succession of the Tertiary Piedmont Basin (TPB) consists, in large sectors, of a chaotic sedimentary body that is related to large scale gravity-driven phenomena, tectonic deformation, gas hydrates dissociation and mud diapirism.

In the SE sector of the TPB very close to a long-lived regional fault (Villalvernia-Varzi Line) that strongly controlled the Oligocene-Miocene sedimentation, several cylindrical carbonate concretions have been recognized 10 to 30 metres below the erosional base of the chaotic deposits within Lower Messinian hemipelagic sediments. Isotopic data indicate that these concretions are strongly <sup>13</sup>C-depleted ( $-59 < \delta^{13}\text{C}_{\text{‰}} < -15$ ), providing a compelling evidence that carbonate precipitation was driven by bacterial degradation of methane. Moreover, the positive  $\delta^{18}\text{C}$  value ( $2 < \delta^{18}\text{O}_{\text{‰}} < 8$ ) suggests that fluids could be sourced from gas hydrates dissociation. These concretions are interpreted as carbonate, cemented fluid conduits originated below the sediment water interface.

Masses of methane-derived carbonates containing remains of chemosymbiotic organisms (Lucinid bivalves and Vestimentiferan tube worms) have been recognized in the chaotic deposits themselves just above the cylindrical concretions. These carbonate masses originated on the sea floor and are the surficial counterparts of the above described chimneys.

The spatial distribution of the chimneys and of the fossil-bearing masses along tectonic discontinuities can provide a detailed three-dimensional reconstruction of an ancient seep field. The distribution of the chimney is controlled by a network of mesoscopic fractures and faults sub-perpendicular to bedding and parallel to the orientation of the shear zones associated to the Villalvernia-Varzi Line. This suggests that mesoscopic faults and fractures associated to the Villalvernia-Varzi Line represent a preferential pathway that controlled the upward migration of CH<sub>4</sub> rich-fluids.

At a regional scale, two main “pulses” of faulting activity, associated to the transcurrent movements of the Villalvernia-Varzi Line, may have triggered the gas hydrates dissociation changing the temperature and pressure conditions inside the sedimentary column or opening pathways to the upward rise of deep seated warmer fluids. In turn, fluids delivered by gas hydrates dissociation probably reduced the shear strength of the overlying sediments triggering the large scale gravity driven phenomena responsible for the emplacement of the Messinian chaotic deposits.

## Creep monitoring on the Mam Tor landslip

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A continuous recording of landslide displacements is often required in order to understand better the complex relationship between triggering factors and the dynamics of the movement. An ideal field site is the impressive Mam Tor landslip, near Castleton in North Derbyshire (UK), formed over 3000 years ago on an oversteepened slope left after the last ice age. A section of the lower mudstones and overlying sandstones have collapsed, leaving an 80 m high scar on the eastern side of Mam Tor. The slip is about 950 m long and over 350 m at its widest extent and has the old main road (A625) from Manchester to Sheffield built across it.

We established the geometric pattern of continuous creep motion at Mam Tor using annual electronic distance measurement surveys since 1996. The average movement rate of the whole mass is about 14 cm per year, with the central region moving significantly faster, at almost 50 cm per year. Over the 190 years since the construction of the highway the creep has led to extensive damage to the road, culminating in its closure in 1979.

A crude correlation between landslip movements and monthly rainfall levels can be demonstrated but this resolution does not allow the precise relationship of rainfall (and hence groundwater levels) to movement to be determined. To resolve fully the relationship between climatic factors and individual movement events data has to be collected to millimetric precision continuously and to this end real time monitoring equipment has recently been installed on the Mam Tor landslip. A monitoring station is used to record the rainfall, air pressure and temperature. Four piezometers and four 2-axis inclinometers installed in two boreholes are used to measure the changes in groundwater levels and internal readjustments within the landslip. An array of three extensometers is used to record individual creep events within the landslip and can also measure the total movement of the landslip.

The results to date show a direct relationship between rainfall events and fluctuations in the groundwater levels with the pattern of antecedent rainfall proving the strongest constraint. The inclinometers show continuous movement of the landslip proving both the overall movement downslope and internal readjustments. The extensometers reveal that the landslip moves with a non-linear relationship to rainfall. At low rainfall levels the landslip creeps slowly but when the rainfall breaches a threshold defined by the antecedent rainfall a creep event is triggered. The non-linearity of movement is a function of the antecedent rainfall, how long a rainfall event lasts and the (low) permeability of the ground, as full connectivity of groundwater needs to build vertically through the landslip to trigger a creep event.

## **Polymodal faulting in subducting slabs by the interaction of compressive anticracks**

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Brittle faults in the upper crust are widely held to be composite shear fractures formed through the interaction and coalescence of tensile microcracks. One mechanism for subduction seismicity below 300 km is phase transformation faulting through the interaction and coalescence of compressive anticracks filled with transformed spinel. The geometry of these flaws and their surrounding elastic stress fields exert a fundamental control on the orientation of the final shear planes. The Coulomb-Mohr failure criterion predicts the development of conjugate bimodal shear planes inclined at an acute angle to the maximum compressive principal stress and parallel to the intermediate principal stress. However, Coulomb-Mohr theory is incapable of explaining more complex three-dimensional fracture populations that are widely observed in rocks and recorded in subduction zone seismicity in which multiple sets of shear fractures are oriented oblique to the intermediate principal stress direction. Previous models of anticrack interaction have employed some form of simplifying two-dimensional approximation. Our fully three-dimensional model is based on the solution of Eshelby. We show that the elastic stress fields around compressive anticracks in three-dimensions promotes interaction and coalescence to form shear planes oriented oblique to the remote principal stresses, and can therefore account for polymodal fault patterns. The variations in the orientation of focal mechanisms is therefore seen to be of primary significance and reflects the oblique nucleation of shearing under truly triaxial stress conditions in the downgoing slab.

## Faults, fluid flow & uncertainty

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Faults affect fluid flow in hydrocarbon reservoirs on multiple length and time scales. Sampling of subsurface information is limited to spatially extensive but low resolution seismic data and sparse, high resolution well penetrations. Large ( $\geq 10\text{m}$  displacement) faults are usually avoided as a drilling hazard and very rarely cored, while typical seismic surveys are designed to image sub-horizontal reflectors rather than faults. This lack of knowledge must be filled by making inferences from indirect data (inverse modelling) and/or by employing some kind of conceptual model to predict fault properties from other information.

In siliciclastic sediments, the type of fault rock developed depends mostly on host rock composition and, to a lesser extent, deformation conditions and temperature history. Fault permeability may be measured from small faults in core, faults in analogue outcrops or synthetic faults created in laboratory deformation experiments. Fault rock relative permeabilities may sometimes need to be modelled, depending on well/fault pattern, production mechanism and simulation parameter of interest.

Observed pressure differences, 4D seismic data, well tests, analogues and history matching may all be used to calibrate fault property predictions, although a change of scale is often required between empirical models and dynamic data. A prerequisite of any method used to optimise properties is knowledge of the range of values within which a particular property (e.g. fault permeability) may occur. Within limits, fault permeability seems relatively insensitive to strain, suggesting that statistics measured from small faults can be extrapolated to similar larger features, provided that mean and variance are corrected to account for *in situ* stress and sample support respectively.

In addition to fault rock property uncertainties, model uncertainty occurs for 'geometrical' parameters (sedimentary architecture, structure geometry, fault geometry). Fault properties may make a significant contribution to overall uncertainty, although the choice of modelling approach is highly dependent on data quality and the problem under investigation.

Further work is required:

- To better define representative ranges for fault property values (fault permeability, thickness).
- To investigate flow sensitivity to spatial variations in fault permeability and thickness.
- To integrate fault and sedimentary uncertainties for reservoir modelling.
- To evaluate different upscaling/downscaling approaches for fault permeability.
- To quantitatively calibrate fault property predictions from dynamic data.

## Spatial variation in fault curvature and slip patch segmentation

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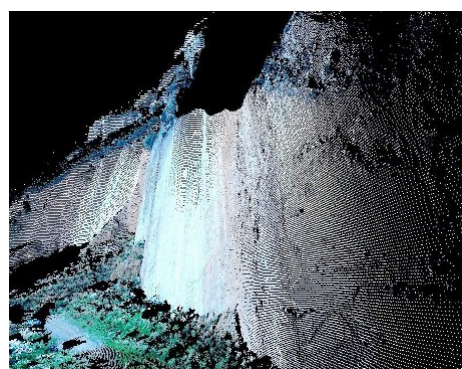
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Fault plane morphology is often oversimplified at all scales in most fault models despite its influence on the mechanical behaviour of a fault. Existing failure criteria for rocks typically assume that fractures are planar and there is little available theory to explain the mechanics of fracture surfaces that are curved. This is at odds with field observations of naturally occurring fracture systems, in which individual surfaces are often observed to be significantly non-planar.

Our observations of curved fractures include examples recorded at a wide variety of scales, from small-scale fractures seen in outcrop, to regionally significant active faults studied in the field and imaged with 3D seismic reflection data. Outcrop examples encompass a range of different lithologies and include opening mode joints, shear fractures and major faults with large measurable offset.

We use terrestrial laser scanning (ground-based LiDAR) to carry out detailed measurements of the 3D geometry of well exposed fracture surfaces. The data provide unprecedented detail and allow spatial variation in various curvature parameters (such as normal, mean and Gaussian curvature) to be quantified. Recent laser-scanning work confirms the following qualitative observations made during previous field studies: many fractures are significantly curved; fracture curvature can include areas of cylindrical, elliptical and hyperbolic geometry (where Gaussian curvature is zero, positive and negative, respectively); fractures can curve repeatedly through the mean orientation, to give sinuous fault traces, in which the dip direction changes along the length of the fault.

The Arkitsa fault zone is located in an area of active extension along the North Evia Gulf in Greece, and has well preserved exhumed fault planes and large cumulative slip. Laser-scan data suggest that some areas of high curvature on fault planes can be caused when smaller slip patches coalesce to form larger fault panels. There is also evidence that the intersection of separate fracture patches can cause slip to be concentrated upon a curved composite surface that combines sections of both the individual intersecting patches, leaving large sections of relict patch remaining in the hanging wall of the newly developed fault. However, some slip still clearly localises on these relict patches, causing disruption of the through-going fault plane in the region around the branch-line. Furthermore, the presence of multiple slicken-line vectors on the exposed surface of the faults emphasises the 3D complexity of deformation in this region, and also raises the possibility that non-plane strain is accommodated by a range of slip events that occur on a number of possible combinations of fault patches, different permutations of which are linked at any given time.



Terrestrial laser-scan of 60m high well exposed curved fault slip-patches at Arkitsa, Gulf of Evia, Greece

## **Uplift and erosion of the Bristol Channel-South Celtic Sea Basin**

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The Birmingham group has established that kilometres-scale exhumation (uplift and erosion) affected the sedimentary basins of southern Britain during the Cretaceous and Cenozoic driven by horizontal shortening of formerly extensional basins (inversion). This exhumation has profound implications for the landscape, physiography, geological structure, hydrology and petroleum prospectivity of the British Isles. To date, our studies have focused largely on the use of thermal history proxies, like apatite fission track analysis and vitrinite reflectance, and also on sedimentary porosities, to constrain the magnitude and timing of the exhumation. The next step is to map in 2D and in 3D the thicknesses of the eroded stratigraphy, and to quantify the amount of shortening generated by the basin inversion episode(s), and thereby test the results from the thermal history data. However, quantifying inversion-related shortening is difficult because the shallowest reaches of the inverted basins (i.e. shallower than the so called null point), where inversion structures would have been most pronounced, are themselves eroded and therefore not preserved.

Flexural isostatic modelling software is being employed in this project to forward model the accumulation of the 'post-rift' successions of selected basins. Comparison of the final stratigraphic geometry indicated by the modelling will allow us to ground-truth information on the magnitude and timing of exhumation obtained independently from thermal history and sedimentary porosities data. However, this is an iterative process because the forward models will be constrained using information on the timing of exhumation episodes from the thermal history data.

In this study, we present results from the Bristol Channel and contiguous South Celtic Sea basins. Forward models are based on basin-normal cross-sections that have been constructed using onshore geological maps, seismic data, including the deep-imaging BIRPS SWAT profiles, borehole logs and field observations.



## Ramping a flat; emphasizing some basic thrust terminologies

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It is common knowledge that thrusts and (to a lesser extent) normal faults often follow non-planar, staircase trajectories that form primarily at the time of fault initiation. Segments of the staircase trajectory are universally called flats and ramps although there remains some ambiguity in their definition, which may sometimes lead to shortcoming in the usage of terminology. The most common usage defines flats as those parts of the fault that are parallel to bedding or other surfaces (e.g. a regional foliation) whereas another definition recommends the usage of the term for datum parallel rather than necessarily bedding-parallel, to extend it to previously deformed rocks or crystalline basement, where the flat is assumed to have been horizontal at the time of fault initiation. In practice, most workers adhere to the first usage, assuming that many fault segments have been rotated by later imbrication or deformation events and do not keep their original attitude with respect to the horizontal. There is no problem with this definition when layers were all horizontal or undeformed prior to faulting. However, labelling ramps and flats may not be a non-trivial matter where they cross angular unconformities (Fig. 1) or basement-cover interfaces as they do in many fold-thrust belts (e.g. Zagros, Pyrenees). However, in fold-thrust belts, where syn-kinematic sedimentation (growth strata) prevails, onlap and angular unconformities are likely to form over eroded anticline. During progressive evolution of such anticlines, bedding parallel slip may occur in the limbs. This localizes deformation along discrete horizons that project or even cut upwards across the younger unconformable units. Such cases test the definition of flats and ramps since the thrust remains parallel to the bedding (both in the hanging-wall and the footwall) where it steps up from the basal decollement (traditionally defined as a ramp). This thrust cuts across the bedding and the unconformity (like a ramp) only where it displaces the unconformable units. Sand-box models and natural examples are used to emphasize the need for consistency in the choice of the datum throughout a geological cross-section. This is particularly advisable, where layering began faulting with different attitudes (Fig. 1).

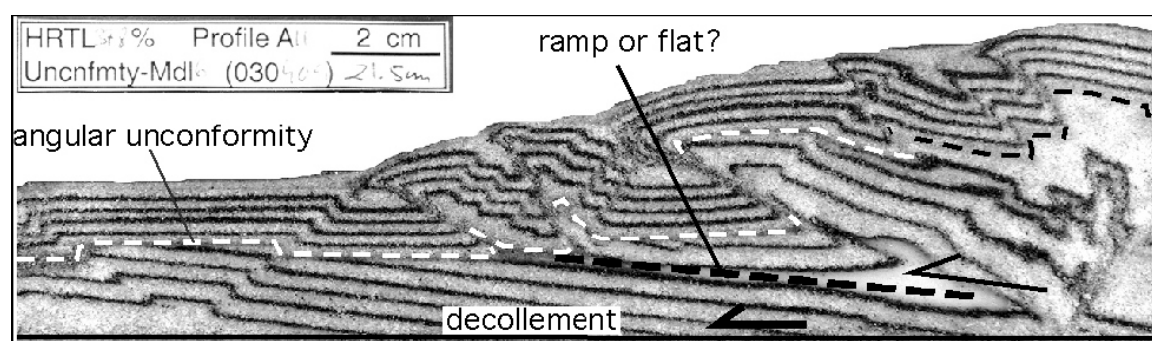


Figure 1. Model section showing deformed unconformable units. Note that the ramp in the tilted layers is bedding parallel both in the hanging-wall and footwall.

## **Giant evacuation structures in the Storegga Slide Scar, offshore Norway – evidence for catastrophic fluid release?**

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Giant crater-like evacuation structures have been discovered in the Storegga Slide scar in the Norwegian Sea, offshore Norway. These structures are tens of kilometres wide. Here we utilise three 3D seismic cubes and one 2D seismic data set to review the distribution of these structures with respect to the regional geology.

Mapping of these structures show that they are always found at the top of the Oligocene-Miocene Brygge Formation. This unit consists of bio-siliceous oozes. These features are termed ‘evacuation structures’ because they are sometimes associated with overlying mounds of bio-siliceous ooze which well data suggest are sourced from the Brygge Formation. It is found that these evacuation structures are normally associated with the crests of Miocene folds, a little above a fossilised Opal-A – Opal-CT transition. The Miocene-Pliocene Kai formation is always locally absent above the structures, so the Brygge Formation is always overlain by the Pliocene-Pleistocene Naust Formation where evacuation structures are found.

A possible hypothesis is that these features may be the result of catastrophic fluid release. This fluid flow may be related to the expulsion of fluid expected as a consequence of the local fossilised Opal-A – Opal-CT transition. Further work is being carried out determine (a) whether these structures are the result of fluid release, (b) when these features formed, (c) whether these features may have been a trigger for retrogressive slope failure, and (d) whether these features present a geo-hazard in the area today.

## **The complexity of exhumation processes in a fossil subduction system provided by the tectono-metamorphic history of the oceanic Lento unit (Northern Corsica)**

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The Alpine Corsica (France) is characterised by a stack of continent- and ocean-derived tectonic units, known as Schistes Lustrés complex. This complex is affected by deformation and metamorphic imprint achieved during Late Cretaceous – Early Tertiary subduction-related processes connected with the closure of the Ligure-Piemontese ocean and subsequent continental collision between Adria and Europe. The Lento unit, belonging to the Schistes Lustrés complex, includes a Jurassic ophiolite sequence and the related sedimentary cover, characterised by complex deformation history associated to HP/LT metamorphism. The accretion-related structures are mainly represented by the S1 foliation, preserved only in the microlithons where relicts of HP minerals can be observed (phengite, lawsonite, Na-amphibole). The exhumation-related deformations started with the D2 phase characterised by isoclinal F2 folds with N30° axes. The syn-D2 assemblages are represented by chlorite, phengite, quartz, albite, Ca/Na-amphibole and epidote. The facing of the F2 folds indicates a tectonic transport normal to the belt-trend. The D3 phase is characterised by asymmetric F3 folds with approximately parallel geometry, showing N-S axes and high-angle axial planes. The related S3 foliation can be classified as crenulation cleavage, with low-grade metamorphic mineral assemblages. Finally, the D4 phase is characterised by parallel, open F4 folds with flat lying axial planes. No metamorphic assemblage related to D4 phase have been observed. The D1 peak conditions can be estimated as  $P = 0.80 \pm 0.20$  GPa and  $T < 450$  °C. The transition from D1 to D2 metamorphic assemblages record a decompressional but near isothermal path from blueschist to greenschist facies. Although the estimated P decrease from D1 to D2 phase suggests the onset of an exhumation processes, the structural features of the D2 phase do not show any evidence of extension. In fact, the D2 phase seems to be developed during the first stages of exhumation by a further shortening event. The switching of the tectonic transport direction from D1 (belt-parallel) to D2 (belt-normal) is referable to a strain-partitioning processes in an oblique subduction setting. The following D3 phase can be connected with a further shortening event characterised by asymmetric E-verging folds, probably related to the beginning of the continental collision. The D4 is originated from vertical shortening and folding, during a ductile extensional tectonics. The data collected suggest that the exhumation process is more complex than previously described and includes three events acquired by different mechanisms. The first two phases of exhumation, i.e. the D2 and D3 phases, were acquired as result of continuous shortening that affected the orogenic wedge during the intraoceanic subduction up to the inception of continental collision. In this picture, only the last D4 phase shows structural features referable to extensional tectonics.

## **Dual petrological and strain-path controls on the seismic anisotropy of deformed continental crust**

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Recorded seismic anisotropy due to lattice preferred orientation (LPO) of elastically anisotropic minerals (especially micas and amphiboles) may be interpreted in terms of strain trajectories in deformed continental crust. Such usage assumes that LPO and seismic anisotropy indicate foliation and lineation. This assumption is tested using plausible rock compositions, microstructures and strain ellipsoids typical of different 3D strain paths to predict the in situ seismic response of deformed crust. For typical polymineralic lithologies, the bulk seismic anisotropy depends upon individual mineral modal content and LPO modulated by the single crystal elastic properties. Here we assume single foliations that parallel components of the 3D strain trajectories. Content can be varied progressively and proportionately for constant LPO to investigate how changing composition impacts on seismic anisotropy. Such ‘rock recipes’ indicate large seismic anisotropy values for micaceous rocks (e.g. schists) and smaller seismic anisotropy values for mafic middle-to-lower crust compared to felsic middle crust. Although deformation impacts also on LPO, the relative strengths of planar and linear features may not be recognised, with concomitant implications for seismic anisotropy, as shown via modified Flinn Plots. Both micas and amphiboles appear sensitive to finite strain, rather than infinitesimal strain, strain magnitude and strain path. For micaceous rocks, LPO and the resultant seismic anisotropy chart the orientation of the XY plane (foliation) but do not record the complete intensity or shape of finite strain ellipsoids. In contrast, amphibole-rich rocks generate seismic anisotropy that give a complete (XYZ) description of 3D strain trajectories. The strain attributes are key for establishing the structural geometry of deformed terrains and underpin traditional kinematic studies at outcrop. The challenge now is to take these methods into the subsurface using seismic anisotropy as a proxy for different deformation states.

## **An experimental investigation of the deformation of sub-glacial sediment from Findelengletscher, Switzerland**

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The work of Engelhardt (1978) and Boulton (1979) demonstrated the deformation of un-lithified sub-glacial sediment beneath the Blue Glacier, Washington and the Breidamerkerjökull Glacier, Iceland. It may be inferred that this observed sediment deformation could accommodate basal sliding of a glacier.

The possibility of sub-glacial sediment deformation beneath Findelengletscher, Switzerland was examined experimentally to determine if this process could provide a mechanism for the flow of the glacier. A direct shear soil testing apparatus was used to simulate sub-glacial sediment deformation under ice thicknesses up to 160m, consistent with maximum ice thicknesses of Findelengletscher of 200m (Iken and Bindschadler 1986).

Measurements of the shear stress, normal stress and % volume change during deformation were derived from the experimental data and analysed using critical state soil mechanics. A Mohr-Coulomb failure model was developed from the measured shear strengths to determine the shear stresses above which failure of the sediment, subsequent sediment deformation and glacial slip may occur.

Driving shear stress and effective stress data (from ice thickness and water pressure) from studies of the glacier by Iken and Bindschadler (1986) and Iken and Truffer (1997) indicated a minimum effective stress of 0.598 MPa beneath the glacier and an average basal driving stress of 0.14MPa. Under these conditions the experimentally derived Mohr-Coulomb failure model indicated that a basal driving stress of at least 0.3MPa would be required to initiate sediment deformation.

The experimental data therefore imply that sediment deformation beneath Findelengletscher could not accommodate glacial slip, without a twofold increase in the basal driving stress of the glacier or an increase in water pressure beneath the glacier to levels far beyond those as yet observed.

An alternative explanation for glacial slip may involve decoupling at the ice-sediment interface at lower water pressures than those required to induce sediment failure, as suggested by Iverson *et. al*, (1995) for the soft bedded Storglaciären, Sweden.

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## **Tectono-metamorphic evolution of the external continental units of Alpine Corsica (France): evidence for involvement of the Europe/Corsica continental margin in the Alpine subduction zone.**

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The Alpine belt in Corsica is characterised by the occurrence of a continental units stack (External Continental Units - ECU), located along the boundary between two main geological domains, referred as Hercynian (to the west) and Alpine Corsica (to the east) respectively. This units stack represents a slice of the Europe/Corsica continental margin, involved in the Alpine orogeny. The investigated area is located in the Northern Corsica, where five main units have been recognised. The ECU include basement rocks (Permian granitoids and their Palaeozoic host rocks), Late Carboniferous-Permian volcano-sedimentary deposits, Mesozoic carbonate deposits, coarse-grained polymict breccias and middle Eocene siliciclastic turbidite deposits. These units record a polyphase deformation history, characterised by superimposed foliations and folds structures well developed in the meta-sedimentary cover. The basement rocks are characterised by heterogeneous deformation with development of localised shear zones, where granitoids show a LT cataclastic-mylonitic deformation. The three main deformation phases can be regarded as ranging in age from Late Eocene (the age of the flysch involved in the D1 phase) to Early Miocene (the age of the oldest deposits found in the Francardo–Ponte Leccia Basin). The occurrence of Alpine polyphase deformation suggests that all the ECU extending between the *Nappe Supérieure* (ophiolitic units affected by very low-grade metamorphism), the Francardo–Ponte Leccia Basin (Early Miocene) and the “autochthonous” domain of Hercynian Corsica were involved in the Alpine Orogeny. Moreover, the occurrence of the peak metamorphism characterised by blueschist P-T conditions, indicates that Alpine HP/LT metamorphism also affected these continental units (previously regarded as weakly- or non-metamorphosed), with estimated P–T conditions of  $T=340\pm40$  °C and  $P=0.75\pm0.15$  GPa for the granitoid rocks from the Castiglione region and  $T=335\pm65$  °C and  $P=0.95\pm0.25$  GPa for the meta-sedimentary cover from the Balagne region. Therefore, this study provides new quantitative data about the peak metamorphism in the Alpine Corsica, where also the eastern margin of the “autochthonous” domain is affected by Alpine deformation and metamorphism. The structural features and metamorphic conditions of the D1 phase, recognised in the ECU, can be interpreted as related to the deformations achieved during their underplating at different depth into the accretionary wedge (as testified by the HP/LT metamorphism), while the D2 and D3 phases can be related to the exhumation history. Particularly the D2 phase was associated to the first stage of exhumation driven by a syn-contractual westward thrusting onto the eastern margin of the Hercynian basement and the D3 phase can be interpreted as related to the last stage of exhumation during the Oligo-Miocene extensional tectonics. As a whole, a continuous belt of continental slices characterised by HP/LT metamorphism of Tertiary age can be identified from the Tenda Massif (NE of studied area) to the Corte area (S of studied area). This picture supports the hypothesis that large portions of the Europe/Corsica continental margin were deformed under HP/LT metamorphic conditions during their involvement in the tectonics connected with Alpine subduction and were subsequently juxtaposed against the metamorphic and non-metamorphic oceanic units during a complex exhumation history.

## **Miocene basin development, tectonic burial and exhumation in the southern Apennines fold-and-thrust belt (Italy)**

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The complex tectonic evolution of the southern Apennines (Italy) is unravelled by integrated structural, stratigraphic and sedimentological studies, together with seismic interpretation tied with well logs and the use of a series of thermal and thermochronological indicators (vitrinite reflectance, clay mineralogy, fluid inclusions, apatite fission tracks) coupled with thermal modelling.

The E-directed southern Apennines fold-and-thrust belt includes both Mesozoic-Tertiary carbonate platform and pelagic (Lagonegro Basin) successions, together with unconformable Miocene siliciclastic deposits. Collectively, these rocks form a highly displaced allochthon that has been carried onto a footwall succession essentially continuous with that of the foreland Apulian Platform. Thermal indicators suggest that parts of the outcropping allochthonous units had been buried to depths in excess of 5 km. Apatite fission-track data indicate a Late Miocene (< 12 My) onset of exhumation of such deeply buried rocks. This process probably involved buttressing of the allochthonous wedge against the outer crustal ramp of the inherited rifted margin of the Lagonegro Basin (i.e., inner ramp of the Apulian Platform). This was followed by linked low-angle extension/thin-skinned thrusting associated with collapse of the gravitationally unstable allochthonous wedge, coupled with basement-involved inversion and reverse faulting at deeper levels (i.e. in the buried Apulian Platform).

The pre-existing tectonic setting is recorded by a pattern of Lower to Middle Miocene basins resting on Mesozoic-Paleogene substrata and containing syn-tectonic accumulations of turbidite sands and related deposits. These include thick sandstones, some derived from reworked cratonic sediments (e.g. the quartz-arenitic Numidian Flysch) and some from crystalline basement from adjacent mountain belts (e.g. Gorgoglione Flysch). The basins were tectonically controlled, in part by NE-directed thrusting and in part by chiefly left-lateral, NW-SE strike-slip. The complex kinematic regime of the southern Apennines during this time period reflects the pattern of 3D slab roll-back in the proto Tyrrhenian-Apennine orogen.

## Fast diffusion along mobile grain boundaries in calcite

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Experimental measurements of grain boundary diffusion are usually conducted on static boundaries, despite the fact that grain boundaries deep in the Earth are frequently mobile. In order to explore the possible effect of boundary mobility on grain boundary diffusion rates we have measured the uptake of  $^{44}\text{Ca}$  from a layer of  $^{44}\text{Ca}$ -enriched calcite powder during the static recrystallisation of a single crystal of calcite at 900C. A region of about 500  $\mu\text{m}$  wide adjacent to the powder layer is heterogeneously enriched in  $^{44}\text{Ca}$ , and complex zoning patterns, including sharp steps in composition and continuous increases and decreases in  $^{44}\text{Ca}$  content, are developed. In metamorphic rocks, these would normally be interpreted in terms of changes in pressure or temperature, Rayleigh fractionation, or episodic fluid infiltration. These explanations cannot apply to our experiments, and instead the zoning patterns are interpreted as being due to variations in grain boundary migration rate. We have applied an analytical model which allows the product of grain boundary diffusion coefficient and grain boundary width ( $D_{\text{GB}}\delta$ ) to be calculated from the grain boundary migration rate and the compositional gradient away from the powder layer. The value of  $D_{\text{GB}}\delta$  in the mobile grain boundaries is at least five orders of magnitude greater than the published value for static boundaries under the same conditions. In order to allow the scale of chemical equilibrium (and hence textural evolution) to be predicted under both experimental and geological conditions, we present quantitative diffusion-regime maps for static and mobile boundaries in calcite, using both published values and our new values for grain boundary diffusion in mobile boundaries. Enhanced diffusion in mobile boundaries has wide implications for the high temperature rheology of Earth materials, for geochronology, and for interpretations of the length- and time- scales of chemical mass-transport. Moreover, zones of anomalously high electrical conductivity in the crust and mantle could be regions undergoing recrystallisation such as active shear zones, rather than regions of anomalous mineralogy, water- or melt-content as is generally suggested.



## **Microstructures of eclogite facies garnet poikiloblasts from the Monte Rosa Nappe, North-Western Italian Alps**

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Garnet is a ubiquitous constituent of rocks that occur at the base of thickened continental crust, within subducted crustal slabs, upper mantle peridotites and the mantle transition zone (majoritic garnet) at depths of 400-650km. Their presence may be significant enough here to play some part in the control of mantle rheology. It is also a key mineral in metamorphic rocks. This is most evident in the high-pressure, high-temperature rock, eclogite. Thus understanding the behaviour of this rock in high-strain conditions is critical to understanding both deformation and metamorphism in the crust (subduction and collision zones) and upper mantle.

The Monte Rosa Nappe is mainly composed of paragneiss and forms part of the internal Alpine chain which contains the eclogite facies zones. In the paragneisses the mineralogy is mainly phengite, garnet and quartz. The garnet comes in two generations a pre-deformation and post-deformation set. Within the pre-deformation garnets there exist two generations of fractures both associated with the retrogression of this unit.

Electron backscatter diffraction analysis of these garnets reveals little to no ductile deformation within the garnet itself. Across both generations of the fractures there is no rotation and generally less than one degree misorientation. These fractures are thought to have formed due to release of elastic strain during unroofing of this unit. The process that they formed under is likely sub-critical fracture propagation.

The first generation fractures are defined by a garnet fill that has a higher Ca concentration than the host grain. The second generation is filled by a retrogressive assemblage. The reasoning for the garnet fill being richer in Ca is due to the fracture acting as a weakened plane along which diffusion occurs more readily. Ca has a slower diffusion rate in garnet than Fe or Mg. Also biotite growth zones associated with retrogression of this unit act as sinks for Fe and Mg.

## Mohr circle constructions for quantifying volume-increase in an extensional high strain shear zone

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Intense seismicity and well-developed active and ancient fault systems are common to the Aegean Region. New geological/structural investigation on the island of Kea reveal a probable crustal-scale, detachment-type, subsequently antiformally domed, high strain shear zone present across the whole island that is part of a S-directed detachment system in the Western Cyclades. These settings were probably established during Miocene extension and thinning of the continental crust.

The area of interest, which lies in north-western Kea, comprises a low angle shear zone where ductile to brittle progressive deformation including key stages of this transition can be observed. A several metre thick brittle cataclastic fault zone separates (i) minimal deformation-related microstructures plus ankeritised dolomite in its hanging wall from (ii) (ultra-) mylonitic marbles in the footwall. The faults dip at low angle towards the NNW. The mylonites have a pronounced stretching lineation that has a maximum plunge of ca. 20° - 40° towards NNE, parallel to the overall brittle kinematics extension direction.

Several generations of extension gashes filled with calcite, quartz and actinolite are widespread throughout the mylonitic rocks, schists and gneisses. Locally situated in gneissic schists, some extension gashes with associated flanking folds are rotated into the shearing direction developing trains of elongated boudins over a few meters.

We use the Mohr circle of the Second Kind to quantify the kinematic flow. This illustrates the amount and nature of the finite shear strain in this particular area. Non-rotated, discordant quartz filled veins, spread over the examined area, represent those indicators present before the finite strain was imposed while suitably orientated stretched (boudined) veins are those indicators used to constrain finite strain. As a realistic scenario, one interpretation shows a high non-coaxial component and a vorticity number near to 1 as well as a delta near to 135° thereby indicating simple shear. The undeformed-to deformed-area contrast provides an exciting view of a volume-increase associated with the input of vein-fill material (assuming plane strain and predominantly simple shear). Furthermore, using a dilatancy term, we modify the velocity gradient tensor dependent on the stretching rate factor, kinematic dilatancy and vorticity number, to illustrate the change in the volume increase with changing amount of shear strain and at various (i.e. increasingly greater) pure shear components.

Ongoing investigations into the mechanical behaviour of the boudined veins as well as chemical rock and vein-fill material analyses will help quantify the most realistic scenario for volume-increase for our model.

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## **Age of Cowhythe Gneiss, NE Scotland: evidence for a Grenvillian tectonic slice within the Grampian terrane.**

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The Cowhythe Gneiss, near Portsoy in NE Scotland was regarded by Read (1955) as high grade Dalradian metasediment in the footwall of the Banff Nappe, tectonically emplaced during the Caledonian Orogeny. Sturt *et al.* (1977) saw the gneiss as the base of a thrust sheet, i.e. in the hangingwall of the Banff Nappe, first metamorphosed during the Cadomian (Pan African) Orogeny (~700 Ma) and then thrust into the Dalradian stratigraphy during the Caledonian Orogeny. New SHRIMP U-Pb zircon analyses show that the Cowhythe Gneiss was migmatized during sillimanite grade regional metamorphism during the Grenvillian Orogeny at 1012 +/- 10 Ma confirming an allochthonous origin. Age dating of inherited zircons in the migmatite indicates mostly early Grenvillian (~1100 Ma) acid magmatic protoliths, together with minor input from Mesoproterozoic, Paleoproterozoic and Archean sources. Two main conclusions are drawn from this data. Firstly, the Dalradian "sequence" in NE Scotland is indeed tectonically mélanged along the Portsoy Lineament. Secondly, Cowhythe Gneiss and its correlatives in NE Scotland, together with the Annagh Gneiss Complex in the W of Ireland can be regarded as part of the basement to the Dalradian sedimentary cover and can provide the Grenvillian detritus that so characterises it. Thus a purely N American provenance for Dalradian sediments is no longer necessary.

## Occurrence of pseudotachylyte in the Sierra Nevada (California)

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Pseudotachylytes are the result of friction-induced melting during seismic slip along a fault, and therefore they represent unique features that allow us to identify and possibly date fossil seismic events. Although models of heat production in fault zones during a seismic event predict that for typical seismic slip rates of ~1 m/sec, temperatures should rise sufficiently to cause melting of the wallrocks, pseudotachylytes have not been widely reported in the literature. This poses the question are pseudotachylytes (i) rare (and therefore the frictional heat dissipation during slip is poorly constrained) or (ii) difficult to preserve, given the delicate nature of glass. We suggest here a third possibility - that pseudotachylytes are difficult to identify unambiguously in the field and, when observed, rarely reported in the literature.



As an example we report the occurrence of pseudotachylytes at Kings Canyon national park in the Sierra Nevada (California). The lithology of the area is dominated by Cretaceous granites cut by steeply dipping faults that are thought to have formed during the Upper Cretaceous. A macroscopic view of the King's Canyon sample shows vein-like structures characterized by a dark grey/black matrix, which cuts a host rock of granodiorite. These vein-like structures range from 2mm to 2.5cm and have a sharp contact with the host

rock with the majority trending diagonally NW-SE across the section. However smaller veins offshoot at high angles to the main fault, which are indicative of the melt origin for these fault rocks. It is difficult to unambiguously characterise these rocks in the field as pseudotachylytes, but observation of these structures under a scanning electron microscope has highlighted the presence of several features that are considered to be diagnostic for defining pseudotachylytes. In particular the presence of microlites within the vein matrix indicate the presence of glass and therefore the occurrence of melting. The microlites range in length from ~50 to 10  $\mu$ m, with the smallest usually being aligned and nucleating directly from the larger microlites. Macro- and micro-scale observations of varying vein colour, clast sizes, and wall rock associations in different zones of pseudotachylyte is evidence for more than one pseudotachylyte generating event. Given that the majority of identification criteria for pseudotachylytes require thin section analysis, it seems likely that field geologists may misinterpret these important fault rocks.

## **Development of crystallographic lattice preferred orientation and seismic properties in the Bhavani shear zone, southern India – a 2Ga history of reactivation?**

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Shear markers and shear sense indicators from the Bhavani shear zone, part of the south Indian Proterozoic shear system that separates the northern Archaean from the southern Pan-African granulite terranes, suggest a history of multiphase reactivation. There is a progressive increase in mylonitisation corresponding to a progression in strain. The LS fabrics indicate near vertical principal flattening planes trending ENE-WSW, but with sub-vertical as well as sub-horizontal stretching lineations implying a reactivation history with dip-slip and strike-slip movement vectors rather than pure flattening. Whilst the SEM-EBSD derived crystal lattice preferred orientation (LPO) of amphibole, biotite and feldspars suggest plastic deformation through the activation of intracrystalline slip systems, diffusional creep accommodated deformation can be inferred from the near-random quartz LPO. All LPO suggest modifications in the fabric due to both retrograde and prograde reactivation during the tectono-thermal history of the Bhavani shear zone over a period of nearly 2.0Ga. In addition, petrofabric-derived seismic properties for the Bhavani shear zone suggest that it exhibits a considerable seismic anisotropy, controlled principally by the LPO of hornblende and biotite. Both LPO and seismic property observations imply conflicting tectonic X and Y directions, indicating possible superposition of contrasting X and Y vectors during different phases of shear zone reactivation.

## **Structural and geomorphological expression of active continental interior transpressional deformation using SRTM 90m topographic data: a case study from the Gobi Altai, Southern Mongolia**

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In this study, we demonstrate the utility of SRTM topographic data as a tool for documenting the distribution of tectonically reactivated crust in the Gobi Altai region of southern Mongolia. The Gobi Altai is characterised by active seismicity, and youthful mountain building which is a distant effect of the Indo-Eurasia collision, 2500km to the south. The topographic data clearly reveal three diagnostic indicators of crustal reactivation: visible fault scarps, sharply defined faulted mountain fronts and Quaternary alluvial fan complexes adjacent to steep mountain fronts. These three variables are combined to produce a new surface tectonic activity map of the region. By analysing mountain front sinuosity and alluvial fan topographic roughness, the tectonic activity of individual mountain fronts is quantitatively compared and ranked. By selecting terrain with slope thresholds between 1-8 and then applying a topographic roughness filter, alluvial fan complexes are easily discriminated and mapped throughout the region for the first time. This allows clear identification of Quaternary uplifted regions (and associated thrust faults) and the distribution of clastic basins which have experienced a two-stage history; Mesozoic rift fill and Late Cenozoic alluvial sedimentation. The methods employed here complement standard Landsat analysis and ground-based geological studies for documenting the regional distribution of active tectonism and can be favourably applied to other deforming regions.

## **Multi seismic cycle velocity and strain fields for an active normal fault system, central Italy**

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Vertical offsets of Late Pleistocene-Holocene deposits and landforms are combined with slip direction indicators on dipping active normal faults in central Italy to produce velocity and strain-rate fields averaged over 12-18 kyrs for a 5-by-5-km-grid. Maximum strain-rates of  $0.078 \pm 0.0156$  ppm/yr, or  $0.052 \pm 0.01$  ppm/yr across a distance of 63639 metres imply maximum NE-SW extension rates of  $5.0 \pm 1.0$  mm/yr or  $3.3 \pm 0.66$  mm/yr depending on whether rates are averaged over 12 kyrs or 18 kyrs. The high spatial resolution reveals that strain-rates vary by up to  $0.04 \pm 0.008$  or  $0.06 \pm 0.012$  ppm/yr over a distance of only c. 7 km along the strike of the fault system, again depending on the timescale chosen. For the first time, these data allow a comparison of rates derived over time periods that would contain numerous seismic cycles with those measured with GPS that represent either interseismic strain, or displacements due to a single large earthquake with some interseismic strain. Overall, the rates compare reasonably well with those measured geodetically or derived from seismic moment summations ( $<0.12$  ppm/yr and generally in the range of 0.10-0.06 ppm/yr; 6.36-3.82 mm/yr). However, the present wide spacing of geodetic sites (30-40 km) means that the small scale spatial variations in strain-rate since 12-18 ka have not yet been resolved using GPS. This makes it difficult to compare strain measured geodetically with that released during historical earthquakes to assess whether excess strain will be released in an impending earthquake.

## **Unravelling the Dinaride orogenic belt of former Yugoslavia: towards a unified tectonic model for the Balkan region**

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Reconstructions of many orogenic belts remain poorly understood, or controversial. A case in point is the Dinarides, located in a critical region (>1000 km E-W) linking the classic Alpine and E Mediterranean regions. Several tectonic models assume the existence of a single Neotethyan oceanic basin, or several simultaneously existing oceanic basins separated by microcontinents, or terranes.

The Mesozoic Tethys (Neotethys) in the region opened by rifting of the Adria/Dinaride continent to S in the Triassic (unrelated to local subduction), and one or more microcontinents drifted towards Eurasia (e.g. Drina-Ivanjica unit). Two important units that include dismembered Jurassic ophiolitic rocks and deep-sea sediments (Dinaride Ophiolite Belt and Vardar Zone Western Belt) may be interpreted as a single regional unit that was emplaced during Late Jurassic-Early Cretaceous time (but excluding Upper Cretaceous ophiolitic rocks; see below). In addition, melanges and ophiolitic rocks, including a dismembered "oceanic arc" unit, existed further N and were accreted to the 'Eurasian' margin (Serbo-Macedonian composite unit) by the Early Cretaceous. Importantly, a wide Tethyan ocean remained open during the Cretaceous. Subduction, collision and southward migration of a collisional deformation front ensued in latest Cretaceous-Palaeogene time.

Occurrences of sub-continental mantle lithosphere (e.g. Zlatibor ultramafic body) are believed to reflect exhumation within an ocean-continent transition zone bordering the Adria/Dinaride continent, as in the Alps and N Atlantic. The Jurassic ophiolites are interpreted as lithosphere generated above a subduction zone during the Early-Mid Jurassic. The melange is seen as a subduction complex in which the main driving force was tectonic accretion (i.e. most of the melanges are not sedimentary olistostromes as widely believed). The driving mechanism of ophiolite emplacement was the collision of a subduction trench with a continental margin (e.g. as for e.g. the U. Cretaceous Oman ophiolite). Much penetrative deformation affecting the melange and ophiolites resulted from post-emplacement deformation related to continental collision (as in Greece and Albania) rather than to initial ophiolite emplacement, as commonly believed.

A tectonic model is proposed in which (in common with Albania and Greece), a SW-dipping subduction zone was activated outboard of the Adria-Dinaride passive margin during the Early-Mid-Jurassic. Ophiolites formed above this subduction zone and melange was accreted within it. Ophiolites and melanges were emplaced northwards over the rifted Drina-Ivanjica microcontinent to the NE by the Early Cretaceous. Further north, subduction beneath the Serbo-Macedonian continent during the Mid-Late Jurassic lead to melange accretion and genesis of an intra-oceanic back-arc basin. A remaining wide ocean basin was subducted northwards during the Cretaceous giving rise to further SSZ-type spreading during the Upper Cretaceous ("Kosara ophiolite"), followed by collision, suture tightening and related strike-slip/transpression.

Robertson, A.H.F. and Mountrakis, D. 2006. Tectonic Evolution of the Eastern Mediterranean Region. Spec. Publ. Geol. Soc. London, vol 260,



## A small look at a big boundary

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Macquarie Island is the only sub-aerial exposure of the Macquarie Ridge Complex, which lies along the Australia-Pacific plate boundary (~158.8°E, 54.5°S). It is a complete but dismembered exposure of oceanic crust uplifted but still rooted in oceanic lithosphere and is unique among ophiolite complexes as it is the only one known to have formed at a mid-ocean ridge and spreading centre. The complex was formed within a series of short (~50km) spreading ridge segments connected by large (>100km) off-set transform faults from 9.5-12Ma (Rivizzigno & Karson 2004, Wertz et al. 2003). After spreading began, the pole of rotation migrated southward but remained close to the plate boundary such that spreading became oblique, resulting in a gradual decrease in ridge segment length through time, as shown by fracture zones, spreading fabric and magnetic anomalies (Wertz et al. 2003). The crustal blocks were then tilted, rotated and uplifted at ~5Ma to form Macquarie Island (Rivizzigno & Karson 2004). The northern part of the island consists mainly of peridotites and gabbros (plus basaltic lava flows, volcanic breccias and sediments), cut by doleritic sheeted dykes, representative of the upper mantle and lower crust (Wertz et al. 2003, Rivizzigno & Karson 2004). It is juxtaposed against the rest of the island, comprising mainly upper crustal basaltic lavas and local sheeted dykes, by the Finch-Langdon Fault. There is evidence (i.e. hydrothermal veining, presence within talus breccias and greywacke sediments) that the gabbros were exposed on the sea floor, which typically occurs at inside-corner:ridge-transform intersections (Wertz et al. 2003). Gabbros adjacent to the Finch-Langdon Fault contain small (<10cm wide), N-NW trending greenschist to amphibolite facies mylonitic shear zones and semi-brittle fault zones (Rivizzigno & Karson 2004). The sub-parallelism of the mylonite shear zones to the main fault suggests that they are related to early fault motion, with initial normal motion followed by oblique slip motion during shearing at the ridge-transform intersection (Wertz et al. 2003). The mineralogical, microstructural and petrofabric-derived seismic characteristics of a sheared amphibolitised gabbro (collected by the late R. Varne) have been investigated in this study. Preliminary results indicate varying degrees of grain size reduction by dynamic recrystallisation and grain boundary migration, within both the shear zone and its immediate wall rock. Distinctive overprinting microstructures and crystal slip systems have been recognised that indicate a complex deformational history initiating with high temperature, low pressure (~3km depth) igneous emplacement, followed by ductile (mylonitic) shearing and ending with a period of retrogressive, low temperature brittle deformation, possibly accompanied and facilitated by injection of late-stage, low temperature fluids. Distinctive seismic signatures for the shear zone and wall rock gabbros are recognised also. Similar history and seismic characteristics are postulated therefore for the main Finch-Langdon Fault.

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## **Deformation by footwall collapse and serial folding in a fold-thrust belt: an example from the Zagros Simply Folded Belt, Iran**

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The Zagros Simply Folded Belt is a well-known, young, fold-thrust belt, ideal for the study of developing deformation in a convergent margin setting. Methods for the analysis of deformation in fold-thrust belts are being developed from the study of processed satellite images, digital elevation models and synthetic river networks. This study has identified fold types, river networks and the associated wind and water gaps in the fold structures.

Both detachment folds characterised by a periclinal geometry and fault-bend folds characterised by long, linear fold hinges occur in the Zagros Belt. The amplification rate of periclinal folds can be defined from theoretical analyses of folding and varies in time and space. At a specific point on the fold the uplift rate varies with time and at a particular time the uplift rate varies along the fold hinge. Fault-bend folds result from relatively uniform uplift of a basement block and do not show the same variation in uplift rate. Wind and water gaps occur as a result of the difference in uplift rate and stream downcutting rate.

River networks in the Zagros form a trellis pattern, where the prominent direction parallels the fold hinges. Major river diversions are spatially associated with folds with high aspect ratios and crossed by multiple wind gaps. These are considered to be fault-bend folds. Fold Front Sinuosity measurements, used as a proxy for age, show that fold structures young to the SW, with anomalously old folds near the major thrust faults. Major steps in the landscape correlate with the long folds and major thrust faults. The faults formed sequentially as the deformation front progressed to the SW, generating the long overlying folds and leading to the alteration of river channels.

It is suggested that the lines of anomalously long folds, marked by lines of wind gaps and major river diversions, are major structures clearly linked to movement along major basement thrusts. Images draped over a DEM clearly show major steps in the landscape, correlating with the long folds, marked by major thrust faults (the High Zagros Fault, Mountain Front Fault and Zagros Frontal Fault). These formed sequentially as the deformation front progressed towards the Persian Gulf. Important pulses of movement on these faults generated the long overlying folds and lead to the abandonment of river channels and the formation of wind gaps.

Within the Simply Folded Belt of the Zagros Mountains relatively small, periclinal detachment folds develop as buckles between the major thrust faults. At the same time movement along the thrusts creates fault-bend folds as the thrusts ramp up through the sediments. Thus as the deformation becomes progressively more difficult and the compressive stresses build up serial folding occurs behind the fault-bend folds in the cover sediments of the overthrust block. Eventually, continual deformation of the block by either thrusting or folding requires stresses in excess of those required to form a new thrust and the original thrust is abandoned. A new fault forms in front of it and the process repeats.

## **Three-dimensional structural and hydrologic evolution of Sant Corneli Anticline, a fault-cored fold in the Central Spanish Pyrenees**

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The Sant Corneli Anticline is a well-exposed example of a fault-cored fold whose hydrologic evolution and structural development are directly linked. The E-W striking anticline is ~5 km wide with abrupt westerly plunge, and formed in response to thrusting associated with the upper Cretaceous to Miocene collision of Iberia with Europe. The fold's core of fractured carbonates contains a variety of west dipping normal faults with meter to decameter scale displacement and abundant calcite fill. This carbonate unit is capped by a marl unit with low angle, calcite filled normal faults. The marl unit is overlain by clastic syn-tectonic strata whose sedimentary architecture records limb rotation during the evolution of the fold. The syn-tectonic strata contain a variety of joint sets that record the stresses before, during, and possibly after fold growth. Faulting in the marl and calcite-filled joints in the syn-tectonic strata suggest that normal faults within the carbonate core of the fold eventually breached the overlying marl unit. This breach may have connected the joints of the syn-tectonic strata to the underlying carbonate reservoir and eliminated previous compartmentalization of fluids. Furthermore, breaching of the marl units probably enhanced joint formation in the overlying syn-tectonic strata. Future geochemical studies of calcite compositions in the three units will address this hypothesis.

Preliminary mapping of joint sets in the syn-tectonic strata reveal a multistage history of jointing. Early bed-perpendicular joints healed by calcite strike NE-SW, parallel to normal faults in the underlying carbonates, and may be related to an early regional extensional event. Younger healed bed-perpendicular joints cross cut the NE-SW striking set, and are closer to N-S in strike: these joints are interpreted to represent the initial stages of folding. Decameter scale, bed perpendicular, unfilled fractures that are sub-parallel to strike probably represent small joints and faults that formed in response to outer arc extension during folding. Many filled, late stage joints strike sub-parallel to, and increase in frequency near, normal faults and transverse structures observed in the carbonate fold core. This suggests that faulting in the underlying carbonates and marls significantly affected the joint patterns in the syn-tectonic strata.

## Fault rock generation & fault core evolution in densely welded ignimbrites

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There are a number of mechanisms proposed for fault core growth and the generation of fault rocks (breccia & gouge). In the wear model of Scholz (1987) abrasion and attrition that occurs during frictional sliding results in a linear increase in wear material volume with increasing displacement. Power et al (1988) invoked the roughness of fault surfaces and increasing mismatch between these surfaces with increasing displacement, as a mechanism of isolating larger asperities to form breccia and gouge. Childs et al. (1996) suggested that tip-line and asperity bifurcation leads to complex fault cores with several slip planes and localised variations in fault core thickness as the segmented tip-line encloses lensoid bodies of rock of varying sizes. Factors that may influence which processes occur in any given fault include lithology, confining-pressure at time of faulting and rate of fault propagation. These mechanisms predict an overall increase in fault core width with displacement.

We present a new model of fault core growth and fault rock generation from an investigation of faults cutting densely welded ignimbrites in Gran Canaria Spain. The faults, ranging from 12 cm to 22 m of displacement allow us to examine the evolution of the fault core through time. Our model predicts that fault core growth, fault morphology and breccia clast size are controlled by pre-existing joints in the ignimbrite unit. The fault core grows by the incorporation of joint delineated slabs. Thus joint spacing will control slab width and the amount the fault core expands by during a slip event. Furthermore, joint spacing is itself controlled by the intrinsic rock fabric formed as a result of ignimbrite deposition; the fabric also exerts a control over breccia clast shape within the core. The fabric present in densely welded ignimbrites is a result of extreme flattening of fiamme to form cm thick sub-mechanical layers within the larger unit. Joints are more closely spaced where these sub-layers are present. The intensity of compaction decreases moving upwards in a unit and therefore so too does the presence of sub-layers and joint density. This is mirrored in the structure of the fault core. Our model suggests that rock fabric is a major influence on the intensity of deformation elements, fault core growth and the components of the fault core.

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## Endglacial seismotectonics in Swedish Lapland: the Parve Fault revisited.

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The Lapland Fault province presents a spectacular example of deglaciation seismotectonics, with postglacial rebound of northern Fennoscandia 9000 years ago apparently triggering a swarm of prominent reverse fault-scarps (Lagerback 1979, Muir Wood 1989). The most extraordinary of these is the Parve Fault, which boasts a postglacial rupture length of 160 km and vertical displacements up to 15 m, consistent with rupture in a magnitude 7.6 earthquake. Microseismicity associated with this lineament indicates that the fault remains active, and reveals a steep basement structure that extends down to 40 km depth (Arvidsson 1996). The basement itself comprises a strongly heterogeneous Proterozoic (1.6-2 Ga) crustal fabric riddled with major shear zones, an inherited structural pattern which appears to exert a control on postglacial reactivation (Talbot 1986). The nature of this influence, however, remains enigmatic; while some postglacial faults align with segments of known mega-shears, others - including the Parve Fault - appear not to conform to any mapped ancient basement structure. Also, it remains unclear why some shear zones are ripped open by postglacial faulting while neighbouring ones are not. In part, the nature of basement control on recent fault reactivation is obscured by the patchy exposures of Precambrian bedrock within an extensive terrain mantled by postglacial debris, but equally the ambiguity reflects a perplexing lack of detailed geological investigation of these remarkable structures.

Here, we report on a reconnaissance visit to the Parve Fault for an integrated research investigation that will explore pre-existing structural controls on its postglacial reactivation. The focus of the study is the northern segment of the rupture zone, where the fault scarp is best pronounced and where relatively continuous tracts of bedrock are revealed by fault displacement. Preliminary mapping of probable postglacial fault scarps in the region of the eastern end of lake Tornetrask suggests a more complex pattern of structural reactivation involving cross-structures. This apparent segmentation of the fault zone raises the critical question of whether the Parve scarp is indeed a single-event feature or whether it is the cumulative product of a chain of more moderate magnitude ruptures. A key to resolving this issue is precise dating control on the timing of fault movement, which currently relies only on relative stratigraphic evidence and lacks absolute radiometric ages. In this regard, we outline a proposed programme of study that aims to better constrain the fault history of the Parve Fault.

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## Why fractured clasts?

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**Fracture architecture.** Fractured clasts in gravels and conglomerates occur in numerous areas and in very different geological settings, ranging from Caledonian orogens to Late Neogene fluvial terraces. A common feature of strata bearing fractured clasts is their occurrence close to the map-scale faults. It follows that the fracturing is, at least partly, tectonic. Fracture architecture can be either well-organized or poorly-organized. One reason for poorly-organized architecture is common occurrence of *in situ* formed neofractures and fractures inherited from mineralised joints cutting host strata in the source area. It follows, that the longer is sedimentary transport from the source area, the lesser is the share of inherited fractures and the fracture architecture is better organized. However, if the joints in the host strata in the source area are not mineralised, the fracture architecture can be well-organized even in case of short sedimentary transport. The fracture architecture is independent of clasts: lithology, size, shape and orientation. The architecture of tectonic fractures is different to that of frost- induced fractures. The last one is largely controlled by clast fabric.

**Fractured clasts and timing of faulting.** The age of clast fracturing constrains timing of related faulting. Within gravels, the fracturing is restricted to clasts. The matrix is not fractured. Therefore, the age of gravels constrains the timing of related faulting. The timing is fairly precise in case of the Pleistocene and Holocene fluvial terraces. When fracturing affects indurated conglomerate, the resulting fractures affect both clasts and matrix. It follows that in conglomerate the clast-restricted fracturing formed before induration of the conglomerate. The rate of induration depends on the type of the cement. Calcite cement induces rapid induration.

**Fractured clasts and kinematics of faulting.** Kinematic interpretation of fractures is rather difficult even if the fractures show well-organized architecture. The interpretation is easier when the fractured clasts bearing strata are affected by either clast-scale or exposure-scale other tectonic features (folds, dykes, faults) or by map-scale folds.

**Fractured clasts and earthquake risk.** Fractured clasts have been observed in numerous areas of recent and historical seismicity. Consequently, the origin of fracturing is believed to be related to earthquakes. The evaluation of the earthquake risk is especially difficult for the areas with a long recurrence interval of earthquakes. The main reason is short historical and instrumental record. It appears, that extending the period of observations by including the geological record of earthquakes may facilitate the evaluation of earthquake risk. Moreover, the occurrence of fractured clasts in the surficial strata can be used for mapping blind faults in the basement.

## **Does deformation saturate seismic anisotropy?**

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The progressive simple shear deformation that characterizes ductile fault zones in the crust involves both rotation and intensification of the strain ellipsoid. These mathematic predictions have been confirmed repeatedly by finite strain determinations in outcrop studies of natural shear zones and used to test geodynamic models of mountain belts. Seismic anisotropy (SA) methods offer the opportunity to pursue these approaches in situ. First however, we must calibrate the magnitude and orientation of the SA ellipsoid against naturally deformed tectonites of known strain state and microstructure. Here we present data from a field analogue of mafic ductile crust in an amphibolite-facies shear zone developed in a deformed mafic dyke embedded within the Lewisian Gneiss (Badcall, NW Scotland). Deflection of pre-existing linear and planar elements and attenuation of the dyke into the shear zone are used to determine the strain gradient. Specimens collected along this gradient were used to establish the geometric fabric intensity defined by different minerals (hornblende grain alignment and ellipticity of plagioclase clots). Finally, petrophysical properties were calculated for the specimens using the SEM-EBSD measured populations of lattice preferred orientations (LPO) for all mineral phases. It is the hornblende-plagioclase LPO, combined in their modal proportions and modulated by the individual mineral single crystal elastic properties, which define the SA profile across the shear zone. Hornblende develops a strong preferred dimensional orientation and hence LPO at shear strains of  $\sim 2$ , whereas the plagioclase LPO remains close to random regardless of bulk strain. The modelled SA of the samples is dominated therefore by the amphibole LPO. Although the values of bulk shear strain vary across the shear zone (0 at the margins to  $>12$  in the centre), the calculated intensity of SA saturates at a shear strain of  $\sim 2$ . These results, if typical of large-scale in situ shear zones, suggest that the orientation rather than intensity of SA is the key tool for charting strain trajectories in mafic continental crust.

## **Tectonic analysis of the Siberian Altai (2003) earthquake**

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A  $M_w$ 7.3 earthquake occurred in September 2003 in the actively evolving Altai Mountains of Siberia, near the Russian-Mongolian border. In this remote and exposed area, the surface expression of the earthquake and the major tectonic structures are well preserved, making it an ideal natural laboratory for analysing and understanding the relationships between major seismic events and regional neotectonics.

A high quality SAR interferogram (InSAR) has been derived from two cross-event Envisat ASAR datasets, which reveals significant co-seismic deformation emanating from a pronounced NW-trending rupture zone in the south-western Chuya Basin. Quantitative measurement reveals that at least 3 metres of displacement has occurred in the slant direction, which inverse modelling suggests is caused primarily by right-lateral slip on a wrench fault. In addition, it was found that the rupture geometry is strongly controlled by rock type. The surface rupture trace is linear in basement rocks of the Chuya Range but curves as it crosses the poorly consolidated sediments of the basin. This may be related to the formation of second-order helicoidal fractures in the cover rocks generated by displacement on the underlying basement fault. Combining the results from radar interferometry with detailed structural investigations using Landsat ETM+ images, it is apparent from the abundance and co-existence of strike-slip, oblique-slip and thrust faults, that the Siberian Altai is actively deforming under transpression.



## **Fluid composition of quartz veins: a proxy for a progressive upper-crustal deformation history. Examples from Central Armorica, Brittany, France.**

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The Monts d'Arrée slate belt, situated in the western part of the Central Armorican Terrane (Brittany, France), is the result of a predominantly contraction-dominated deformation during the late-Palaeozoic Variscan orogeny. Rocks affected belong to the Lower-Palaeozoic Plougastel formation, consisting of a siliciclastic multilayer sequence. Primarily based on cross-cutting relationships with structural features, such as bedding, cleavage, and folds, seven different quartz-vein generations could be identified and placed within the time frame of the deformation history. They reflect a changing degree of kinematic control, ranging from pre-cleavage, bedding-perpendicular, parallel vein arrays confined to the quartzite layers (type 1), to post-cleavage, transverse, massive quartz veins (type 7).

Microthermometry and Raman analysis of the fluid inclusions in the vein-quartz enabled to track the evolution in composition of the fluids involved. Primary fluid inclusions show a gradually changing composition in the different vein generations. It is an aqueous-gaseous  $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}-\text{CH}_4-\text{N}_2$  fluid. The methane content increases from type 3 to type 6 vein quartz. Secondary fluid inclusions, present in clusters and trails, show, however, a rather homogeneous aqueous-gaseous  $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}\pm\text{CH}_4$  composition, followed by an aqueous  $\text{H}_2\text{O}-\text{NaCl}$  fluid. The composition of the fluid is identical for all vein generations. This fluid is enriched in  $\text{CO}_2$ , depleted in  $\text{CH}_4$  and lack  $\text{N}_2$  with respect to the primary fluids that circulated through the rocks. The presence of large amounts of non-polar species in both primary and secondary fluids, furthermore, indicates an intense fluid-rock interaction.

The gradually changing composition of the primary fluid within the different vein generations suggests that the composition of these fluids may serve as a proxy for the progressive deformation history of the Monts d'Arrée slate belt under evolving metamorphic conditions. The later, homogeneous  $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}\pm\text{CH}_4$  fluid that pervasively circulated through the rocks of the Plougastel formation, may possibly be related to the massive quartz veins within the transverse fracture system. This late-tectonic fluid flow event still bears a clear metamorphic signature (high  $\text{CO}_2$  content), indicating that it still occurred within the contraction-dominated deformation conditions of the Monts d'Arrée slate belt.

## On the formation of bedding-perpendicular and bedding-parallel quartz veins in the Variscan fold and thrust belt: late burial or early tectonic?

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Veins have frequently been studied in compressively deformed areas. Although veins, having formed pre-buckling and -thrusting, have an important impact on the paleo-rheology of rock, early veins have often been neglected in structurally complex systems. We present preliminary results on early vein formation in the Variscan fold and thrust belt, and discuss their formation with a genetically paleo-stress model.

The research area is situated in the north-eastern, anchizonal, peripheral part of the High-Ardenne slate belt, situated in the frontal zone of the Central European Variscides. The Rursee area, located in the North-Eifel (Germany), exposes an upper-Pragian to lower-Emsian siliciclastic multilayer sequence, characterised by the occurrence of numerous quartz-vein generations. The area consists of closed, angular, NW-verging, overturned, syn-cleavage, folds with varying fold hinges plunging to the north-east and to the east.

Two different vein sets can be recognised that pre-date buckling. The first set consists of at least 3 generations of *bedding-(sub)perpendicular* quartz veins (1) which continue across fold hinges. The majority of the veins are confined to the competent, coarse-grained, psammitic beds. Sometimes, these veins exceed the competent bed. In those cases, vein refraction occurs at the competent-incompetent interface with the pelites. Their shape varies from straight, thin, hairline veins to curved thick, multifractured veins in which as well elongated as blocky quartz crystals are present. Macro- and microstructural analysis reveal that these thick (maximum 10 cm wide) veins are the result of several fracture and sealing events, and suffered a complex subsequent deformation history, indicating an early, pre-Variscan development. The *bedding-parallel* quartz veins (2), both present at the interface of beds of contrasting lithology as interbedded in pelitic and psammitic beds, have a complex internal fabric, consisting of different generations of quartz laminae intercalated with brecciated host rock fragments and thin pelitic slices. These bedding-parallel veins do crosscut and thus post-date the bedding-(sub)perpendicular vein set (1). Both vein sets are overprinted by progressive folding, forming the characteristic overturned folds and the development of an axial planar slaty cleavage. This cleavage fans out against the bedding-parallel quartz veins, which indicates that also the latter vein set predates the main Variscan fold- and cleavage-development.

Further research efforts will concentrate on the microfabric analysis of these vein sets and the microthermometry of the fluid inclusions of vein quartz with the aim to contribute to the discussion on the true origin of bedding-perpendicular and bedding-parallel veins.

## Sheath folds, shear fabrics and kinematic indicators of magma flow during emplacement of silicic dykes: a case study from Arran, Scottish Tertiary Igneous Province.

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Microfabrics, orientated vesicles and anisotropy of magnetic susceptibility (AMS) are commonly used to infer magma flow direction and emplacement mechanisms of basalt dykes<sup>1,2</sup>. However, rhyolite dykes commonly exhibit abundant folds, lineations and kinematic indicators<sup>3</sup> that can be readily documented in the field and used to make inferences about magma emplacement and flow direction. Hitherto, this type of analysis has been applied to silicic lavas and rheomorphic ignimbrites<sup>4,5</sup>, but not to dykes.

Structural analysis of a flow-banded Tertiary rhyolite dyke ('Judd's No. I') on the Isle of Arran reveals local shear sense and magma flow directions. The 9 m – 14 m wide dyke is exposed in plan view for a distance of 180 m and can locally be seen in vertical section. Devitrified (lithoidal) margins, <2 m thick, enclose a vitrophyre (pitchstone) central part, <2 m thick. Flow lamination is best seen in zones of partial devitrification, < 6 m thick. Detailed mapping reveals that the flow lamination generally lies sub-parallel to dyke margins and is extensively folded on mesoscopic and microscopic scales. Early formed structures include isoclinal, intrafolial sheath folds<sup>5</sup> and inclined folds with axes sub-parallel to pervasive extensional lineations. Late-nucleated folds are open and have axes at various high angles to the predominant lineation direction, indicating that they have undergone less shear and consequent transposition. Lineations vary from slickenline-like structures to large mullions and have an average trend of 27° / 046° (NE). Kinematic indicators, including sigma objects and delta objects in the form of rotated phenocrysts and spiral-shaped magmatic inhomogeneities, indicate consistent magma flow towards the southwest and rising, i.e. parallel to the lineations. The distribution of flow perturbations and well developed lamination across the entire width of the dyke favours laminar flow rather than plug flow, and the presence of abundant refolded sheath folds indicates sustained, progressive deformation. Geochemical analysis of vitrophyre samples reveals a link with the Central Igneous Complex of Arran and, combined with dyke geometry, indicates that Judd's No. I represents part of a cone sheet.

<sup>1</sup>Walker GPL., (2005) Determination of flow directions by combining AMS and thin-section analyses: implications for Oligocene volcanism in the Kerguelen Archipelago (southern Indian Ocean) – *Geophysical Journal International* Vol. 160 Issue 1 p63

<sup>2</sup>Liss D., Hutton DHW., Owens WH. (2002) Ropey flow structures: a neglected indicator of magma flow direction in sills and dykes. *Geology* 30: 715-718.

<sup>3</sup>Vernon R.H. 1987. A microstructural indicator of shear sense in volcanic rocks and its relationship to porphyroblast rotation in metamorphic rocks. *Journal of Geology* 95: 127-133.

<sup>4</sup>Andrews, GDM, Branney MJ (2005) Folds, fabrics, and kinematic criteria in rheomorphic ignimbrites of the Snake River Plain, Idaho: insights into emplacement and flow. In Pederson, J, and Dehler CM (eds) *Interior Western United States: Geol. Soc. Amer. Field Guide* 6, 311-327.

<sup>5</sup>Branney MJ, Barry TL, Godcheaux M. 2004. Sheathfolds in rheomorphic ignimbrites. *Bulletin of Volcanology*, 66: 485-491

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