UNIVERSITY OF BIRMINGHAM

TSG

6th-8th January 2010
School of Geography, Earth and Environmental Sciences
University of Birmingham
Birmingham UK
B15 2TT

www.gees.bham.ac.uk/tsg2010.shtml

Causes of basin inversion, Blue Ben, Somerset (photo C. Stevenson)

Tectonic Studies Group 2010 Birmingham

We are delighted to welcome you to the annual meeting of the Tectonic Studies Group for 2010 at the University of Birmingham, Wednesday 6th to Friday 8th January.

The meeting venue is the Avon Room, 2nd floor University Centre (building R23 on the map inside the back cover)

Those arriving on Tuesday evening (5th) are welcome to join us for a drink in the Lapworth Museum of Geology (building R4, by the Ring Road).

Contents of this volume:

The Lapworth Museum of Geology and Earth Sciences department (Photo: J. Clatworthy)

Organisers:

Carl Stevenson
Tim Reston
Sam Spendlove
Ken McDermott
Babangida Jibrin

With help from, and many thanks to:

Paul Simpson	Income manager (online shop)
Paul Brew	Senior Conference and Events Coordinator
Lisa Carr	Conference and Events Coordinator
Jon Clatworthy	Curator of the Lapworth Museum
Mike Hansen	Technical services, Psychology (extra poster boards)
Will Cooper	Printing services (abstract volume and name badges)
Steve Swoffer	email access and workshop IT support

And of course thanks to our sponsors; BP, Shell and BG-group
Thanks also to Midland Valley Exploration for contributing to the post meeting workshop – Move2010 for teaching and research (Saturday 9th – see back cover)

2010 meeting program

UNIVERSITY OF BIRMINGHAM

Tuesday 5th January

18 30 onwards — Wine reception in the Lapworth Museum
Registration desk open in Lapworth Museum
Poster hanging

Wednesday 6th January

08 00 – 09 15 — Registration desk open in Lapworth Museum (until lunch)
Arrival tea, coffee and refreshments
09 15 — Welcome – Professor Tim Reston
09 30 — Technical programme day 1 – talks and posters

Session 1: **Reducing uncertainty and risk**		
09 30 – 09 45	*The Freyja project: uncertainty analysis of geological interpretations*	***Euan Macrae**, Clare Bond, Zoe Shipton
09 45 – 10 00	*The influence of Structural and Stratigraphic uncertainties on fault seal analysis and reservoir compartmentalisation of deep water fan systems*	**Wood, A.**, Paton, D, Cook, A.
10 00 – 10 15	*'De-risking the prospect' Incorporating structural uncertainty in petroleum systems modelling: A case study from the Judd Basin, U.K.*	**S. M. Clarke**, H. Johnson & J. Rodriguez
10 15 – 10 30	*Test-driving the Virtual Seismic Atlas – finding analogues and authoring content*	**Rob Butler** and Taija Torvela
10 30 – 10 45	*The number of km-scale impact craters yet to be found on Earth is c. 800*	**Stewart, S. A.**
10 45 – 11 00	Discussion period	

Chair: Nicola De Paulo

11 00 – 11 30 — Break with tea, coffee and refreshments

Session 2: **Neotectonics and active basins**		
11 30 – 11 45	*Afterslip on the L'Aquila earthquake (M6.3) surface rupture captured in 4D using a Terrestrial laser scanner (TLS)*	***Wilkinson M.,** McCaffrey K.J.W., Roberts G., Cowie P.A., Phillips R.J. & Michetti, A.
11 45 – 12 00	*High resolution monitoring of creep of the Mam Tor landslip, Derbyshire*	**Ernest Rutter** and Sam Green
12 00 – 12 15	*Fault Lubrication and Earthquake Propagation in Thermally Unstable Rocks*	**N. De Paola,**T. Hirose, T. Mitchell, G. Di Toro, C. Viti and T. Shimamoto
12 15 – 12 30	*Late Cenozoic reactivation of polydeformed basement in the Chinese Beishan region north of Tibet*	**Cunningham** Dickson and Jin Zhang
12 30 – 12 45	*Normal-Fault Architecture and Deformation Processes in Poorly Consolidated Sediments within an Actively Extending Basin, Gulf of Corinth, Greece*	***Sian Loveless**, Victor Bense and Jenni Turner
12 45 – 13 00	Discussion period	

Chair: Steve Jones

13 00 – 14 30 Lunch and posters

Session 3: **Palaeostress and brittle tectonics**		
14 30 – 14 45	*Combination of paleostress and paleomagnetic data: case studies from the Pannonian Basin*	**Fodor**, L.I., Márton, E
14 45 – 15 00	Seismites reveal long-term earthquake behavior of the Dead Sea Fault	**Shmuel Marco**
15 00 – 15 15	*The stress state of the brittle upper crust during early Variscan tectonic inversion and its influence on high-pressure compartments*	**Van Noten, K.**, Muchez, P. & Sintubin, M.
15 15 – 15 30	*Characterising brittle reactivation in basement: an example from the Lewisian Gneiss Complex, NW Scotland*	***J. C. Martin**, R. E. Holdsworth, K. W. J. McCaffrey, A. Conway & M. Krabbendam
15 30 – 15 45	*Palaeostress reconstruction in the Lufilian Arc and the Kundulungu foreland (Katanga, Democratic Republic of Congo): in search of evidence of incipient active rifting*	***Kipata, M.L.**, Delvaux, D., Sebagenzi, M.N., Cailteux, J.-J. & Sintubin, M.
15 45 – 16 00	Discussion period	

Chair: Steve Rippington

16 00 – 16 30 Break with tea, coffee and refreshments

Session 4: Posters
16 30 – 17 30

Thursday 7th January

08 00 – 09 15 Registration desk open in Lapworth Museum (until lunch)
Arrival tea, coffee and refreshments
09 15 Technical programme day 2 – talks and posters

Session 5: **Mapping and remote sensing**		
09 15 – 09 30	*The origin and evolution of the Cretaceous northwest Sirt Basin, Libya, based on remote sensing interpretation and well data analysis*	***Khalifa M. Abdunaser**, Ken J.W. McCaffrey
09 30 – 09 45	*InSAR mapping of an active Iranian salt extrusion*	**Ian Alsop**, Pedram Aftabi, Mahasa Roustaie, Christopher J. Talbot
09 45 – 10 00	*Geology of the Ordovician Tyrone Igneous Complex, Northern Ireland*	***Cooper, M. R.,*** *Crowley, Q. G., Hollis, S. P., Noble, S. R., Roberts, S., Chew, D., Earls, G, & Herrington, R..*
10 00 – 10 15	*Polyphase deformation in the Lake Hazen region, at 82^{o} north on Ellesmere Island: implications for the tectonic evolution of the High Arctic*	**Stephen Rippington**, Robert Scott, Helen Smyth, Simon Kelly
10 15 – 10 30	*A ruck, a ramp and imbricate stack, but no culmination – the Dundonnell sector of the Caledonian Moine Thrust Belt, Northwest Highlands of Scotland.*	**Leslie, A.G.,** Goodenough, K.M.& Krabbendam, M.
10 30 – 10 45	Discussion period	

Chair: Sam Spendlove

10 45 – 11 15 Break with tea, coffee and refreshments

Session 6: **Margins**		
11 15 – 11 30	*Evidence for Quaternary convergence between the North American and South American plates, east of the Lesser Antilles*	Patriat M., Pichot T., **Westbrook G.K.**, Umber M., Deville E., Bénard F., Roest W., Loubrieu B. and the ANTIPLAC cruise party

11 30 – 11 45	*Thermal weakening localizes intraplate deformation along the southern Australian continental margin*	**Simon P. Holford,** Richard R. Hillis, Martin Hand, Mike Sandiford
11 45 – 12 00	*Structural Controls on the Evolution of the Southeastern Brazilian Continental Margin*	***Ashby, D.E.**, McCaffrey, K.J.W., Holdsworth, R.E., Almeida, J.C.H., Oliver, J.
13 00 – 12 15	*Detachment faults during continental breakup and beyond*	**Tim Reston**
12 15 – 12 30	*Cenozoic history of Britain and Ireland: Implications of modern dynamic support for the Paleocene underplating idea, and quantification of plate boundary drivers of Cenozoic structural inversion*	**Stephen M Jones**
12 30 – 12 45	Discussion period	

Chair: Ken McDermott

12 45 – 14 15 Lunch and posters

Session 7: **Novel approaches and applications I**		
14 15 – 14 30	*Calculated petrophysical properties of rocks from CPO analysis by EBSD in a section across the Moho in Cabo Ortegal (N Spain)*	**Sergio Llana-Fúnez**, Dennis Brown, Ramón Carbonell, Joaquina Álvarez-Marrón, David Martí, Matthew Salisbury
14 30 – 14 45	*Linking sill morphology to emplacement mechanisms*	***Nick Schofield**, Carl Stevenson, Tim Reston
14 45 – 15 00	*Cone sheet emplacement in sub-volcanic systems: a case study from Ardnamurchan, NW Scotland*	***Craig Magee**, Carl Stevenson and Brian O'Driscoll[2]
15 00 – 15 15	*Contrasting magnetic susceptibility fabrics on opposite fold limbs: cause and implications*	**Debacker, T.N.**., Seynaeve, N., Sintubin, M. & Robion, P.
15 15 – 15 30	*Characterising the role of basin margin structure on finite strain patterns across a 'cleavage' front from the Variscides of southern Ireland*	***Parker, C.**, Meere, P., Stevenson, C., Mulchrone, K.
15 30 – 15 45	Discussion period	

Chair: Carl Stevenson

15 45 – 16 15 Break with tea, coffee and refreshments

Session 8: Posters
16 15 – 17 30

17 30 – 18 00 AGM Chaired by Professor John Wheeler
18 00 – 18 30 Wine and posters

19 00 TSG conference dinner, Noble Room, 2nd floor, Staff House

Friday 8th January

08 00 – 09 30 Registration desk open in Lapworth Museum (until lunch)
Arrival tea, coffee and refreshments
09 15 Technical programme day 3 – talks and posters

Session 9: **Novel approaches and applications II**		
09 15 – 09 30	*Fault stepping and drainage evolution in the Corinth basin rift, Greece*	**Turner, J.A.,** Leeder, M.R. and Finch E.
09 30 – 09 45	*A geological investigation into fault weakening mechanisms revealed in deep drill core from the San Andreas Fault Observatory at Depth (SAFOD)*	**Bob Holdsworth**, Esther van Digglen, Hans De Bresser, Steve Smith
09 45 – 10 00	*K-white mica thermo-barometry, conodont colour alteration index and vitrinite reflection: methods to distinguish nappes in a complex diagenetic to low-grade metamorphic nappe pile*	**Kövér, S**. & Fodor, L. I.
10 00 – 10 15	*3D Pulsating flow and possible strain pattern in general shear zones*	**David Iacopini**, Rodolfo Carosi, Paris Xypolias
10 15 – 10 30	*Fault and fracture patterns in low porosity chalk*	**David Sagi**, Nicola De Paola, K.J.W. McCaffrey & R.E. Holdsworth
10 30 – 10 45	Discussion period	

Chair: Tim Reston

10 45 – 11 15 Break with tea, coffee and refreshments

Session 10: **Modelling and strain analysis**		
11 15 – 11 30	*Spatial analysis, structural geology and mineral exploration*	**Julian Vearncombe** and Susan Vearncombe
11 30 – 11 45	*Reconciliation of contrasting theories for joint spacing in layered sequences*	**Schöpfer, M.P.J**., Arslan, A., Walsh, J.J., & Childs, C.
11 45 – 12 00	*3D numerical modelling of the evolution of fault zone internal structure*	Schöpfer, M., Childs, C. & **Walsh, J.J.**

12 00 – 12 15	*Structural modelling of possible contaminant pathways below nuclear installations*	***Richard Haslam**, Stuart Clarke, Peter Styles & Clive Auton
12 15 – 12 30	*Strain analysis from point fabric patterns: A new objective method*	**Lisle, Richard J**
12 30 – 12 45	Discussion period	

Chair: John Wheeler

12 45 – 14 15 Lunch and posters

Session 11: **Seismic analysis, interpretation and integration**		
14 15 – 14 30	*Length-throw relationships in an evaporite-detached extensional fault array: The Bremstein Fault Complex, offshore mid-Norway*	**Wilson, P.**., Elliott, G. M., Gawthorpe, R. L.., Jackson, C. A-L. & Hansen, S.
14 30 – 14 45	*Geological and structural evolution of the Rosaria Mare intraplatform Basin and its tectonic implications (Adria/Apulia plate boundary, SE Italy)*	**Felici, F.**, Turco, E., Pierantoni, P. P., & Milia A.
14 45 – 15 00	*Linking fault geometry with wall-rock deformation: 3-D seismic investigation deepwater Niger Delta*	***Jibrin, B**., Turner, J.P., Westbrook G.K., Bretan, P.
15 00 – 15 15	*Different interpretations of thrust trajectories and strain distribution in a fold-and-thrust belt*	**Torvela, T.,** Butler, R. W. H. & Bond, C.
15 15 – 15 30	Discussion period	

Chair: Nick Schofield

15 30 – 16 00 close

16 00 – 16 30 Departing tea, coffee and refreshments

Saturday 9th January

Post meeting workshop: *Move2010 for teaching and research*
In collaboration with Midland Valley Exploration Ltd.

Midland Valley

Midland Valley Exploration's Academic Initiative's began three years ago and now, between the Field Mapping Initiative and the Academic Software Initiative, nearly 200 academic geosciences departments worldwide are using Move.

This workshop aims to introduce Move2010 to academic users and to highlight a few potential uses in teaching and research. We will go through some hands-on exercises from the Move2010 tutorials and discuss some current uses in academic teaching and research including field mapping.

Contact Carl Stevenson: c.t.stevenson@bham.ac.uk
Midland Valley will be represented by Dr Ruth Wightman

Workshop itinerary:
09.00 - 09.20 Introduction to Move and the rationale behind the ASI
09.20 - 11.00 Move2010 hands-on exercise - 2DMove
11.00 - 11.30 Refreshment break
11.30 - 12.30 Move2010 hands-on exercise - 3DMove
12.30 - 13.30 Lunch (Lapworth Museum)
13.30 - 14.00 Introduction to structural analysis - 4DMove
14.00 - 15.00 Examples of using Move in teaching and research
15.00 - 16.00 Examples of using Move in field mapping
16.00 - 16.30 Refreshment break
16.30 - 17.30 Participant Examples / Q&A

Cost - £7.50 (on arrival)
Places are limited to 30

The Origin and Nature of Cenozoic Faulting in North East Ireland
***Anderson, H**., Walsh, J.J. & Cooper, M.R

The impact of strain, bedding plane friction and overburden pressure on joint spacing
Arslan, A., Schöpfer, M. P. J., Walsh, J. J., Childs, C.

Influence of deep transverse fault zones on the prospectivity, geometry and spatial arrangement on some hydrocarbon-related structures, Zagros fold and thrust belt, northern Iraq
Banks, G.J.

Analysis of structural lineaments and their relationship with paleotension fields responsable for the formation of cenozoic brittle structures, Espirito Santo State (SE Brazil)
***Bricalli, L.L**., *Cianfarra, P., Salvini,F. & Mello,C.L.*

3D modelling of ore deposits geometry in the Variscan basement of SE Sardinia (Italy).
Cristina Buttau, Antonio Funedda, Andrea Dini, Stefano Naitza.

Incorporating structural uncertainty into petroleum systems modelling to reduce exploration risk
S. M. Clarke, M. Littler, H. Johnson, M. Quinn, J. Rodriguez, S. Stoker & P. Ware

The Fluid Flow Evolution During the Seismic Cycle Within Overpressured Fault Zones in Evaporitic Sequences
N. De Paola, *C. Collettini, D.R. Faulkner*

The Cantabrian Thrust Belt: basin history of the North Gondwana passive margin - rifting, glaciation? more rifting then collision.
***Helen Doherty**, *Tim Ferriday, Michael Kelly, Michael Montenari, Steven Rogers & Graham Williams*

Structural evolution and fluid flow in the Wealden and Hampshire basins, southern England, U.K.
***Salah Eldin M. Elgarmadi**, Graham Potts, and Richard Worden

A geometrical relationship between imbricate thrust structures and their generated topography of mass-transport deposits (MTD's); implications for the accommodation of sediment laden gravity-driven flows.
***Fairweather, L. I. D**. *& Kneller, B. C.*

A layer cake model as a stratigraphic classification of mass-transport deposits (MTDs); from palaeo-flow directions and macro-scale structures, Paganzo basins, Argentina.
***Fairweather, L. I. D**., *Kneller, B.C., Dykstra, M. & Milana, J.P.*

Characterising fracture systems within upfaulted basement highs in the Hebridean Islands: an onshore analogue for the Clair Field
***Franklin,B. S. G.,** 2nd Holdsworth R. E., McCaffrey K.J. W., *Krabbendam M., Conway A. & Jones R*

Modelling continental margin extension using combined rigid/deformable plate tectonic reconstructions
Munoz, A.A., **Glover, C.T**., Harris, J.P., Goodrich, M., Hudson, L. & Ady, B.

Laccolithic emplacement of the Northern Arran Granite, Scotland: a new model based on Anisotropy of Magnetic Susceptibility
****Grove, C*** and Stevenson, C. T

Consequences of Anisotropic Poroelasticity due to Fluid-Saturated Damage
Healy, D.

Structural analysis of fold and thrust structures from deepwater west Niger Delta.
Iacopini D., Grimaud J-L., Butler R.W.H.

Application of dip-related seismic curvature attributes to map surface fault geometry: Examples from deepwater Niger Delta
*J**ibrin, B.,** Turner, J.P., Westbrook G.K., Huck, A., & Hemstra, N.

Magma plumbing in the Judd Basin, North Atlantic, from opacity rendered 3D seismic data
***Adam Linnell**, Carl Stevenson, Nick Schofield

Fault-related fracturing in carbonate damage zones: field analysis and modeling from Central Apennines (Italy)
***Mannino I**., Salvini F., Cianfarra P.

How to Form a Rifted Margin – Fault, Fault and Fault Some More
***Ken McDermott** , Tim Reston & Jonathon Turner

Examining the low-angle normal fault system of north-west Kea based on a new geological map
Müller, M.., Grasemann, B. & Iglseder, C.

Interactions between strike-slip faults, Westward Ho!: domino vs conjugate
***Casey W. Nixon**, David J. Sanderson, Jonathan M. Bull and Stephen Dee

Quantification of Curvature and Fracture Distributions in Outcrop-Scale Periclines
Pearce, M.A., Jones, R.R., Smith, S.A.F. & McCaffrey, K.J.W.

The Sardic Phase.
Puddu C.

The interpretation of major fault zone properties using three integrative approaches
Taylor, R.L., Rutter, E. H. & Faulkner, D.R.

The effects of crystallographic anisotropy on fracture development and acoustic emission in quartz
Timms, N.E., **Healy, D.,** Reyes Montes, J.M., Collins, D., Prior, D.J., & Young, R.P.

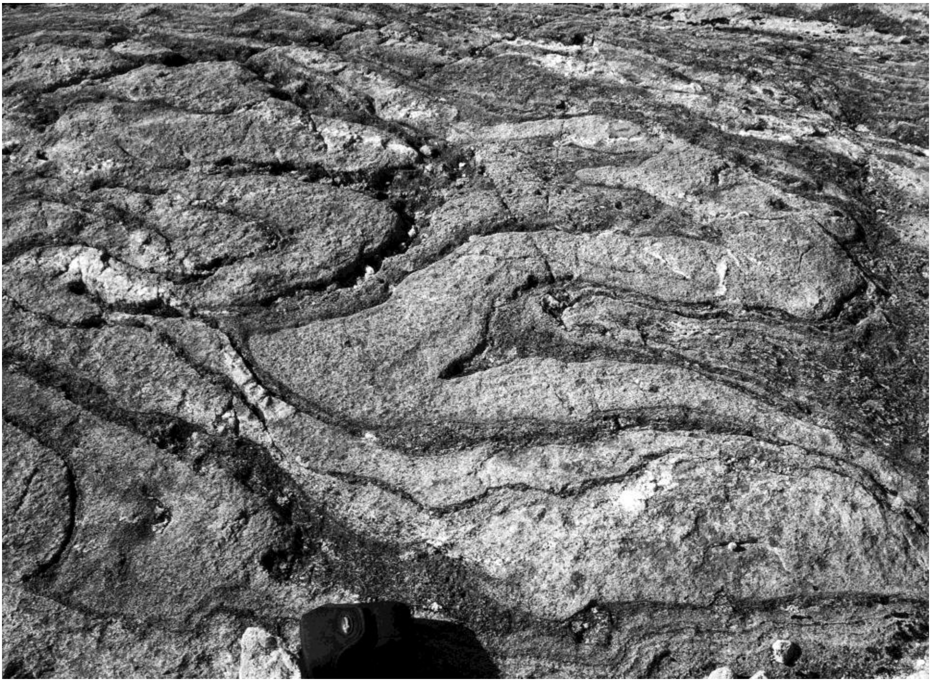
The Virtual Seismic Atlas – utilising web-based material in Earth science research.
Torvela, T. & Butler, R. W. H.

Visualising and understanding structural geology from the field to the lab: using Move as an aid in teaching and research.
Wightman, R.H., Bond, C.E., Scherrenberg, A., Similox-Tohon, D.

* Student presentation

2010 Talk abstracts

UNIVERSITY OF BIRMINGHAM



The Freyja project: uncertainty analysis of geological interpretations

Euan Macrae[1], Clare Bond[2], Zoe Shipton[1]

[1]University of Glasgow
[2]Midland Valley Exploration

Models of sub-surface geology are created from data sets that sample a limited volume of the subsurface and at a limited resolution; therefore, even with modern data collection techniques, the final model is highly dependent on the interpreter's conceptual framework. Interpreters from diverse educational backgrounds, or with experience in a range of oil field settings, can come up with very different results for the same dataset [1]. The ambiguity in the model choice is known as *'conceptual uncertainty'*; it is the uncertainty in the geological concept chosen for the data. Bond et al. found that geoscientists starting with the same dataset produced very different interpretational results and this ultimately affects the final geological model. Understanding why interpreters see particular aspects of a dataset as being important to an interpretation is essential. The Freyja project will statistically investigate the factors that contribute to conceptual uncertainty and then develop interpretation workflows to minimise the associated risk in geological model creation [2].

The Freyja project is part of Euan Macrae's PhD research into geological conceptual uncertainty and *this is a proposal to host an interactive workshop at your conference.* The idea would be to hand out a questionnaire and seismic interpretation exercise (with coloured pens) to be completed voluntarily by the attendees during a talk slot. At the end of the allotted time the questionnaires and interpretations would be collected. Being aware of conceptual uncertainty and its implications will benefit all delegates.

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

2 – Bond et al., 2008, *Structural models: optimizing risk analysis by understanding conceptual uncertainty*, First Break, v26, 65-71.

The influence of Structural and Stratigraphic uncertainties on fault seal analysis and reservoir compartmentalisation of deep water fan systems

[1, 2, *] **Wood, A.**, [1]Paton, D, [3]Cook, A.

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[3] A/S Norske Shell, N 4098, Tananger, Norway

As hydrocarbon exploration frontiers expand into more 'unconventional' settings accurate geological characterisation of potential reservoirs becomes increasingly important when making economically driven development decisions. The use of outcrop analogues has become common within the last 15 years and is now an important and powerful tool for predicting both facies distributions and reservoir properties. One area where application of outcrop data is especially useful is deepwater turbidite systems. Sand body architecture is often un-resolvable in seismic data, and internal heterogeneity can make correlation between wells difficult. The importance of correctly capturing sediment distribution is particularly important in situations where reservoirs are faulted. Lateral and down-dip thinning of sands strongly influences shale distribution along any fault planes developed, and hence their sealing capacity. Ambiguity in fault throw interpretation not only results in differing cross fault juxtapositions but also the degree to which continuous clay smears are developed. In this scenario uncertainty in the net:gross distribution, as well as structural uncertainty, has a strong control on fault controlled reservoir compartmentalisation, and therefore the development strategy employed.

Here we use a deep-water seismic dataset to compare structural and stratigraphic uncertainties associated with the use of different reservoir analogues. Two structural models are constructed and each populated with three different stratigraphies within the reservoir modelling environment. Fault plane properties key to determining the potential for cross-fault flow are compared for each model. Initial results suggest that uncertainty in the fault seal workflow is compounded by uncertainties in the stratigraphic model used, as well as throw uncertainty, and hence an integrated structural and stratigraphic approach to reservoir modelling is suggested.

'De-risking the prospect' Incorporating structural uncertainty in petroleum systems modelling: A case study from the Judd Basin, U.K.

S. M. Clarke[1], H. Johnson[2] & J. Rodriguez[3]
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[2] British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA
[3] OMV (UK) Limited, 14 Ryder Street, London, SW1Y 6QB

Faults, their movement histories, and their three-dimensional relationships are important controls at all scales on hydrocarbon migration within sedimentary basins. As the hydrocarbons industry explores in ever more structurally complex settings, a full, three-dimensional, well constrained, structural interpretation becomes ever more valuable. However, the structural model is an interpretation of available data and therefore often incorporates great uncertainty, particularly during the exploration phase where subsurface data are sparse and sometimes spatially inconsistent. Structural relationships, fault displacement and faulted stratigraphy can in many instances exert the dominant control on the location and volume of predicted hydrocarbon accumulations, and consequently the development of a better understanding of the inherent uncertainties and risks becomes essential.

In this work we develop new statistical and stochastical approaches to the examination of structural uncertainty and its incorporation into petroleum systems modelling in order to reduce exploration risk. We apply these techniques to a prospect from the Judd Basin, west of the Shetland Isles, U.K. in order to delimit those specific uncertainties to which predicted hydrocarbon accumulations are sensitive.

The upper Palaeocene final marine infill of the Judd Basin has been, to date, largely ignored as a possible hydrocarbon play due to the presence of mudstones of slightly older Palaeocene age that are interpreted to form a regional seal. These mudstones are believed to isolate the upper Palaeocene succession from the underlying and proven hydrocarbon play that includes the Suilven, Foinaven and Schiehallion fields. Previous seismo-stratigraphical analysis of the upper Palaeocene succession has identified prospects adjacent to fault-zones where the regional seal may be breached. Significant structural uncertainty exists regarding these prospects including the potential for varied displacement on key faults to provide juxtaposition relationships that breach the regional seal, the varied presence of fault-zone gouge, and the possibility that faults may themselves act as conduits to hydrocarbon migration. These uncertainties, coupled with those related to stratigraphy, result in significant risk for the regional seal integrity and highlight the possibility of migration pathways into an upper Palaeocene play.

From our work we are able to investigate the relative importance of these uncertainties and demonstrate that one uncertainty in particular – the ability for key faults to act as migration conduits – is of crucial importance to the viability of the upper Palaeocene play. Uncertainty in the remaining structural aspects of the model is of a subordinate nature and therefore the key risk associated with the viability of the upper Palaeocene play is manifest in the ability of faults to act as conduits to migration. The presence of hydrocarbon shows within the very limited number of wells that have to date tested the upper Palaeocene succession, therefore suggests that faults do indeed provide valid hydrocarbon conduits. This observation, combined with our risk analysis, opens up prospectivity of the upper Palaeocene play in the Judd Basin and surrounding area and provides a focus for the structural risking of potential prospects within it.

Test-driving the Virtual Seismic Atlas – finding analogues and authoring content

Rob Butler and Taija Torvela

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Aberdeen AB24 3UE, UK

The Virtual Seismic Atlas is a freely accessible internet resource that showcases seismic data and, especially, its geological interpretation. Although it is in essence an image gallery, comprising high resolution jpeg files that may be downloaded, by hosting other documentation and web-links, the VSA is a hub to link subsurface knowledge. Clean and interpreted seismic images may be accessed in "picture and workbook" format similar to existing hard copy atlases but with the advantage of showing multiple interpretations. The rich variety of metadata, geophysical, geographical, contextural and interpretational can be used to locate examples of geological structures. The key application is a database that is interrogated by a search engine powered by Endeca. By using the "Guided Navigation" to search, discover and retrieve images, users are exposed to arrays of geological analogues that provide entirely novel insights and opportunities for research and education. Each step in a multi-dimensional search juxtaposes new combinations of images and different search paths throw up different intermediate results. These structures generate surprising juxtapositions of related content – creating an environment to find analogues structures that the user did not know existed. These functions are openly available to users browsing anonymously. To author content users must register and log onto the VSA. Individuals can then build arrays of clan and interpreted images through a structured authoring workflow. Adding new or competing interpretations of existing images is actively promoted. Authoring takes a few minutes, with new content approved by the VSA management. When logged users also have access to further functionality including personalised favourites lists – a useful tool for sharing content for training courses.

This presentation will show these various functions. The VSA is openly accessible at: www.seismicatlas.org

The number of km-scale impact craters yet to be found on Earth is c. 800

Stewart, S. A.

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The number of accepted impact craters on Earth currently stands at 176, yet other solid bodies in the solar system display vastly more craters. Of course the difference is largely explained by active geological processes on Earth. However the Earth contains enormous tracts of buried sedimentary basin with excellent preservation potential for a wide range of things from fossils to impact structures. Here we tackle the question "how many impact craters are preserved, waiting to be discovered in the sedimentary basins on Earth?" Apart from the intriguing issue of what the total number of preserved craters on Earth might be, this work provides guidelines for the probability of finding impact structures that could be applied in assessing interpretations of unusual structures on reflection seismic data such as the Silverpit, Murshid and Praia Grande structures.

The first requirement is a "crater production function" that estimates the number of craters in terms of crater size and given area of interest and timespan. There are a number of approaches to defining crater production functions; reconciling the known Earth inventory with a range of methods enables (partial!) reduction in uncertainty in the method. The resulting function can be applied to specific cases of crater population estimates, for instance how many craters might be expected in a given area of 3D reflection seismic coverage that contains strata of a given age range. The function applied here is a multi-branch power law that encompasses the filtering effects of Earths' atmosphere, which breaks up relatively small impactors with an increasingly aggressive effect on crater population for craters less than 10 km in diameter. Nonetheless, structures less than 10 km in diameter are of interest in seismic interpretation and this analysis ranges down to minimum crater diameters of 1 km.

To calculate the number of craters yet to be found on Earth we apply the crater production function to an approximate area and age range of strata with suitable preservation potential, and subtract the number of known buried craters. Due to the decreasing preservation of sedimentary basins with increasing age this analysis considers only the Phanerozoic i.e. the most recent 542 Myrs. We also need to account for water depth, which effectively filters the lower end of crater size. The "volume" of sediment is expressed as a product of area and age (km^2yrs). Some 9×10^{15} km^2yrs of Phanerozoic sediment are estimated to be present on Earth, yielding a crater population of 800 craters (excluding the 62 known buried craters). Uncertainties in the crater production function and volume of preserved strata are appreciable, leading to a range in the order of -50% to +200% in this estimate. Nonetheless this is the first attempt to answer this question; further iterations will address uncertainties. The origins of "possible" impact structures (e.g. imaged but undrilled) are revisited in light of this analysis.

Afterslip on the L'Aquila earthquake (M6.3) surface rupture captured in 4D using a Terrestrial laser scanner (TLS)

Wilkinson M.[1], McCaffrey K.J.W.[1], Roberts G.[2], Cowie P.A.[3], Phillips R.J.[4] & Michetti, A.[5]

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Normal faulting earthquakes produce coseismic vertical motions that are expected to amplify during the days and weeks after the mainshock. The amplitude, wavelength and timescales associated with such postseismic deformation can help constrain the seismic cycle and reveal whether the isostatic response to an earthquake is driven by fluid and poro-elastic effects, visco-elastic creep in the mantle or afterslip within a velocity strengthening zone in the shallow crust, or a combination of the above.
Here, we report the results of an innovative survey of the surface rupture formed during the 6th April L'Aquila earthquake (M6.3) using precise 3D terrestrial laser scan (TLS) technology. Using surface modelling techniques, we have produced a 4D afterslip survey across a 3 x 65 m area that has detected millimetre-scale movements on and adjacent to the rupture at exceptionally high horizontal spatial resolution (4cm). We identify and present surface motion observations of two distinct styles. On the surface rupture, we recorded surface motions totalling 14.6 mm slip and this was accompanied by 26.2 mm of continuous vertical subsidence in the form of a 30m wide hangingwall syncline. We model the surface motions from both zones using power law and Nason & Weertman approximations. Both surface rupture afterslip and hangingwall synclines on normal faults have been observed in previous studies but this is the first time the incremental growth of both features has been observed in 4D.
We conclude that surface motions measured from subsidence in the syncline to be indicative of the general postseismic deformation created by initially rapid local afterslip within the shallow portion of the fault zone. The surface motions measured from offsets across the surface rupture is a stick-slip low initial rate response that is retarded with respect to the syncline and thus does not represent the surface motion of greatest magnitude for this event. This is the first time such a discrepancy has been directly recorded and its recognition highlights that traditional survey techniques collecting sparsely distributed surface motion data are insufficient to characterise the true magnitude of surface motions related to afterslip. Empirical datasets of earthquake magnitude, rupture length and surface offset, such as those published in Wells & Coppersmith will have underestimated maximum surface offset, particularly for low magnitude events.
To capture the diversity in styles of afterslip on the hangingwall surface, pertaining to heterogeneous mechanical properties and slip styles within shallow fault zones, as well as identifying the maximum magnitude of afterslip we highlight the need for high-precision and high density monitoring over extended survey areas.

High resolution monitoring of creep of the Mam Tor landslip, Derbyshire

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The Mam Tor landslip (Peak district, Derbyshire, England), some 300m wide and 700 m long, is an actively creeping mass that formed initially some 3500 years ago. Constructed initially in 1815, the main highway between Sheffield and Manchester zig-zagged across it, until in 1979 it was finally closed to traffic as a result of annual damage due to slippage within the body of the landslip and at its margins.

Since 1996 the rock deformation group at Manchester have monitored the distribution of creep of the Mam Tor landslip by means of annual surveying using electronic distance measurement. In this way we have established annual creep rates of up to 50 cm per year, with some indication that creep is accentuated during years of heavy winter rainfall. This approach, however, does not allow sufficiently high resolution correlation between creep rate and groundwater level, therefore in 2005 we completed the installation of three underground, high resolution wire creep meters, an automatic rain gauge and two boreholes, instrumented with groundwater piezometers and tilt meters. Data is collected every three hours using automatic data loggers, and data can be downloaded remotely using mobile telephones.

Within the body of the landslip two 18m long wire creep meters were placed end-to-end, and the third creep wire was positioned across the southern boundary of the slip. The pattern of slip on all three creep meters is similar. In the summer period hardly any creep occurs, but during the winter months they recorded smoothly varying creep displacements of up to 15 cm. Each borehole carries two piezometers, separated by a vertical interval of about 3 m. These show a clear response to each rainfall event, rapidly increasing followed by a slow decay over several days. The time-averaged level of groundwater reflects the integrated frequency and intensity of rainfall. Rapid creep begins when average groundwater level breaches a critical threshold. This level is breached in the wintertime, but very large amounts of rainfall are required to elevate groundwater sufficiently in the summer months to instigate creep. Summer rainfall is inhibited from infiltrating the ground owing to the effects of evapotranspiration accompanying. vigorous growth of grass and ferns during the summer months. The meteorological office program MORECS was used to quantify the effects of evapotranspiration on groundwater infiltration. This study demonstrates directly this aspect of summer vegetation growth in stabilising landslippage.

Using the Coulomb friction law and measured pore water pressures, we computed an effective rheology for the disaggregated mudstone that constitutes the greater part of the volume of the landslip, relating strain rate to effective shear stress. This is very non-linear, such that a increase of shear stress by about 5% enhances shear strain rate by one-thousand-fold. This rate dependence can be expected to apply to other situations in which poorly consolidated mudrocks are sheared, such as in accretionary complexes.

Fault Lubrication and Earthquake Propagation in Thermally Unstable Rocks

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During earthquake propagation in thermally unstable rocks, the frictional heat generated can induce thermal reactions which lead to chemical and physical changes in the slip zone. We performed laboratory friction experiments on thermally unstable minerals (gypsum, dolomite and calcite) at about 1 m/s slip velocities, more than 1 m displacements and calculated temperature rise above 500 C degrees. These conditions are typical during the propagation of large earthquakes.
The main findings of our experimental work are:
1) Dramatic fault weakening is characterized by a dynamic frictional strength drop up to 90% of the initial static value in the Byerlee's range. 2) Seismic source parameters, calculated from our experimental results, match those obtained by modelling of seismological data from the 1997 Cofliorito earthquake nucleated in carbonate rocks in Italy (i.e. same rocks used in the friction experiments).
Fault lubrication observed during the experiments is controlled by the superposition of multiple, thermally-activated, slip weakening mechanisms (e.g., flash heating, thermal pressurization and nanoparticle lubrication). The integration of mechanical and CO_2 emission data, temperature rise calculations and XRPD analyses suggests that flash heating is not the main dynamic slip weakening process. This process was likely inhibited very soon ($t < 1s$) for displacements $d < 0.20$ m, when intense grain size reduction by both cataclastic and chemical/thermal processes took place. Conversely, most of the dynamic weakening observed was controlled by thermal pressurization and nanoparticle lubrication processes. The dynamic shear strength of experimental faults was reduced when fluids (CO_2, H_2O) were trapped and pressurized within the slip zone, in accord with the effective normal stress principle. The fluids were not initially present in the slip zone, but were released by decarbonation (dolomite and Mg-rich calcite) and dehydration (gypsum) reactions, both activated by frictional heating during seismic slip. The dynamic weakening effects of nanoparticles (e.g. powder lubrication) are still unclear due to the poorly understood mechanical properties of nanoparticles at high velocities and temperatures, typical of seismic slip.
The experimental results improve our understanding of the controls exerted on the dynamic frictional strength of faults by the coseismic operation of chemical (mineral decomposition) and physical (grain size reduction, fluids release and pressurization) processes. The estimation of this parameter is out of the range of seismological studies, although it controls the magnitude of the stress drop, the seismic fault heat flow and the relative partitioning of the earthquake energy budget, which are all controversial and still debated issues in the scientific community.

Late Cenozoic reactivation of polydeformed basement in the Chinese Beishan region north of Tibet

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Active deformation associated with the Indo-Eurasia collision north of Tibet covers huge areas of NW China, Mongolia and S and SE Siberia. These regions are dominated by intracontinental transpressional reactivation of Palaeozoic terrane collages. Because of relatively low historical seismicity, the Beishan region between Tibet and the Gobi Altai is generally regarded as tectonically uninteresting from a neotectonic standpoint. However, our preliminary work in the region coupled with satellite image analysis indicates that the region is cut by at least five major sinistral fault systems that are potentially active and which parallel the Altyn Tagh fault which bounds northern Tibet directly to the south. These fault systems generate localised uplifts within the Beishan and show typical geomorphological characteristics of active intracontinental deforming belts such as sharply defined mountain fronts, Quaternary alluvial fan complexes and tilted peneplain remnants. Specifically, the Yushi Shan and Mazong Shan are Late Cenozoic restraining bends that show clear evidence for Quaternary thrusting and uplift. The Dunhuang Block is bound by a major thrust fault that cuts Quaternary fanglomerates. These separate, but discrete deforming belts effectively close the gap between the Gobi Altai-easternmost Tien Shan regions and northern Tibet and indicate that the entire region between Tibet and the Hangay Dome in central Mongolia has been dominated by left-lateral transpressional mountain building in the Late Cenozoic.

Basement rocks in the Beishan region record several major collisional suturing events associated with amalgamation of the Central Asian Orogenic belt. These events are expressed in a remote region north of Liuyuan by kilometre-scale refolded folds of Permian clastic sediments that are spectacular when seen on satellite imagery. The folds were ground verified during summer, 2009 and sedimentary way-up criteria, cleavage-bedding relations and folded quartz veins were also documented to further constrain the fold geometries and deformational history. Detailed mapping of key areas and structural data analysis reveal that the folds initially formed by Late Permian NNE-SSW directed shortening associated with collisional suturing along the western extent of the Solonker Suture. Subsequent dextral transpression along a major terrane boundary immediately south of the Permian basin generated NW-SE shortening and km-scale type-2 refolds.

During all Palaeozoic terrane amalgamation events, the Beishan crustal block was located between the rigid Tarim and North China Precambrian cratons, and more recently between the modern intracontinental deforming belts in northern Tibet and the Gobi Altai. Thus the Beishan's unique position within Asia has led to a particularly complex polydeformational history involving repeated crustal reactivation by both near-field and far-field stresses associated with Late Palaeozoic-Recent collisional events. This talk will summarise our results obtained so far. Follow-up fieldwork is planned for summer, 2010.

Normal-Fault Architecture and Deformation Processes in Poorly Consolidated Sediments within an Actively Extending Basin, Gulf of Corinth, Greece.

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Tectonic uplift of the southern shoreline of the extensional Gulf of Corinth (GoC) basin has resulted in exposures of both intra-basinal and block-bounding normal faults cutting unconsolidated sediments. Previous studies show that faults in unconsolidated sediments can drastically impact fluid flow patterns, potentially acting as conduits, barriers, or a combination of these behaviours. This region provides an excellent opportunity to study fault architecture and deformation processes of faults in poorly consolidated sediment - a component which is essential to increase our understanding of their hydraulic properties.

Systematic evaluations of macroscopic fault architecture and deformation processes have been made at a number of fault outcrops in the GoC. Fault throws are between 50 m and 0.1 m. Lithologies cut by these faults include both homogeneous sections of marls and gravel as well as lithologically highly heterogeneous sections. Impregnation of low viscosity resin at outcrops allowed the collection of hand samples from which thin sections are produced in order to identify grain scale deformation processes. Grain size distributions are also being analysed to potentially identify deformation processes.

Fault cores consist of dragged beds which retain some characteristics of the undeformed source bed. Faults with greater throws comprise an essentially homogeneous core formed by the mixing of contributing beds. Non-spherical clasts tend to orientate in a direction consistent with the overall fault strain. In a few faults notably higher proportions of broken clasts are found than in the corresponding undeformed beds. Beds may be incorporated into the fault core within bounding planes, forming lenses of undeformed sediment. Classic fractured or deformation band style damage zones are rare but secondary antithetic faults are a common feature. Faults in finer sands and marls commonly host slip planes, as well as having minor fractured damage zones. Clay smears in fault cores have also been observed in outcrops with a high proportion of clay in the contributing beds. Despite a number of fault architecture variations, we find a broad correlation between fault throw and width.

Although some fault cores display broken clasts, particulate flow seems the dominant deformation mechanism in most fault cores. Fractured clasts are possibly indicative of greater strain rates or confining pressures in those faults at the time of fault activity. Disparities in fault architecture may further be attributable to the mechanical strength and/or grain size of the sediments. In contrasting lithologies cut by the same fault, there is a higher degree of strain localisation and corresponding increase of fault dips in clays and fine sands than coarse materials. This may also be the cause of lenses and multiple slip planes often observed in faults cutting through variable lithology.

Observations suggest that the overall consistency of architecture and deformation processes of normal-faults in poorly consolidated sediment could be predictable in this region. However, the translation of these structural fault properties to fault hydraulic properties still needs to be determined

Combination of paleostress and paleomagnetic data: case studies from the Pannonian Basin

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Faulting and vertical axis rotation is two aspects of brittle deformation of the crust. The two types of deformation are connected in theoretical and methodological ways. Vertical axis rotation is frequently induced by faulting, while the rotation results in the formation of two (several) sets of faults if the external stress field is maintained. The two types of deformation can be described by two independent methods: fault-slip analysis and paleomagnetic measurements. The independence of the two methods permits that they cross-check each other: their results can not be in contradiction. Thus the combination of the two methods can give more confidence on the description of the brittle deformation of a certain area.

The Pannonian Basin is a good area to test the applicability and limits of the use of the combined paleostress-paleomagnetic method. The paleostress database contains a large number of data (Fodor et al. 1999) while the paleomagnetic measurements demonstrated several phases of regionally important rotations (Márton and Márton 1996). Giving the young (Miocene to Pliocene) age of rotations and faulting, the investigated deformation phases was not superimposed and only moderately obliterated by successive events.

The Pannonian Basin was born within the Alpine-Carpathian-Dinaridic orogene during the Miocene. The basin formation is due to several driving forces: a continuous ~N–S shortening between the African and European plates, eastward lateral extrusion from the compressed Alpine region toward the Carpathians, eastward pull exerted by the roll-back of the subducted lithosphere, and the rise of the astenosphere beneath the basin. The eastward extrusion was connected to large-scale rotations and penetrative faulting.

The comparison of paleomagnetic and fault-slip data was carried out in two levels; within the same sites and small sub-areas of the Pannonian Basin. Two major counterclockwise rotations occurred in the central–north-eastern part of the basin between 18-17 and 16-14.5 Ma. Correspondingly, three fault sets were detected in Neogene and older rocks; their formation precedes, intercalates and post-dates the two rotation phases. The calculated paleostress axes show an apparent clockwise change, the angle of the two changes is basically the same as the angle of rotations. This suggests that the presence of three sets of faults is due to vertical axis rotation, and the regional shortening direction remained closely N-S during the whole process. In the north-easternmost part of the basin a younger, 12-11 Ma rotation occurred locally, which is reflected in the presence of two fault systems.

In the western part of the Pannonian Basin a third, late Miocene to early Pliocene rotation has been detected. Four brittle faulting events can be connected with these rotations. However, on a more regional scale it is not clear how the youngest rotation was accommodated. In the south-western part of the basin only a 30 counterclockwise Pliocene rotation was detected. Because the fault pattern does not show two phases, and the magnetisation was post-folding, (tilting), the faulting seems to precede the rotation. In this area, large clockwise rotation was measured in a major strike-slip zone. This is reflected by rotated conjugate faults occurring within the shear zone.

In conclusion, the rotation phases and the fault systems show good correlation. Considerable problem arises with paleomagnetic data from late Miocene rocks, whose tectonic interpretation is still not unequivocal.

Seismites reveal long-term earthquake behavior of the Dead Sea Fault

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Rock units that exhibit earthquake-triggered deformation are called Seismites. We study seismites in laminated (varved) lake sediments of the Lisan Formation, dated 70-15 ka, and in subsequent Dead Sea deposits that accumulated within the Dead Sea Fault zone. The interpretation of the Late Pleistocene breccia layers as seismites rely on direct stratigraphic link of to fault rupture events. Similar types of breccia in the Holocene Dead Sea deposits correlate remarkably well with historical earthquakes. The correlation is based on combining radiocarbon dating, varve counting, and critical reading of historical records. The association with surface ruptures is regarded as evidence of earthquake magnitudes of at least 6. The long, almost continuous record shows that the earthquakes come in clusters of 8-12 kyrs separated by periods of reduced activity of similar lengths.

An inherent ambiguity associated with the similar effect of nearby moderate earthquakes and distant strong earthquakes is partly resolved for breccia layers that are overlain by gypsum layers. Geochemical considerations indicate that gypsum was deposited from the lacustrine brines following overturn and homogenization of the otherwise stratified water column in the lake. Modeling of earthquake ruptures at the bottom of the lake and in the vicinity of the lake shows that only strong earthquakes at the bottom were capable of generating seiche waves that mixed the water column, causing the precipitation of gypsum.

In an effort to better understand the physical process that culminates in the formation of breccia and possibly assign sizes to the ancient earthquakes, we arrange the various types of seismites according to the degree of strain. We note that the various types show evolutionary sequence starting in laminar, moderate folds, billow-like asymmetric folds, coherent vortices, and turbulent chaotic breccia. Power spectral analysis of the deformation indicates that the geometry robustly obeys a power-law of -1.89, indicative of turbulence in various environments. Numerical simulations are performed using properties of the layer materials based on measurements of the modern Dead Sea sediments, which are a reasonable analogue of Lake Lisan. The simulations show that for a given induced shear, the smaller the thickness of the layers the greater is the turbulent deformation. This happens because although the effective viscosity increases (Reynolds Number decreases) the bulk Richardson Number becomes smaller with decrease in the layer thickness. The latter represents the ratio between the gravitational potential energy of the stably stratified sediments and the shear energy generated by the earthquake. Hence for thin layers the shear energy density is larger and the Kelvin-Helmholtz instability mechanism becomes more efficient. The peak ground acceleration (PGA) is related to the shear triggered during the earthquake. Hence, a linkage is made between the observed thickness and geometry of a deformed layer with its causative earthquake's PGA.

Combining all the palaeoseismic records from three different segments of the Dead Sea Fault we realize that they all lie on the linear extrapolation of the frequency-magnitude relation of the modern instrumental record. The calculated b-value (the slope of the frequency-magnitude relations) for all three segments is between 0.85 and 1, similar to other major strike-slip faults in the world. We conclude that the Gutenberg-Richter distribution is a stable mode in the Dead Sea Fault during the last 70,000 years.

The stress state of the brittle upper crust during early Variscan tectonic inversion and its influence on high-pressure compartments

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In the frontal part of the Rhenohercynian foreland fold-and-thrust belt (High-Ardenne slate belt, Eifel, Germany), two successive types of quartz veins, oriented normal and parallel to bedding, are interpreted to reflect the late Carboniferous tectonic inversion affecting the siliciclastic Ardenne-Eifel basin at the onset of the Variscan orogeny. Fracturing and sealing occurred in Lower Devonian multilayer sequences in upper-crustal levels. This study aims at constraining pressure-temperature conditions of both vein types, to be able to reconstruct the conditions of fossil high-pressure compartments during early Variscan tectonic inversion.

A detailed structural analysis shows that the bedding-normal veins developed in a regional consistent stress field under low differential stresses controlling the regional quartz vein alignment. Precipitation occurred in equilibrium with the host rock under low-grade, anchizonal metamorphic conditions with maximum burial temperature up to 250°C. In the vein fill, quartz commonly occurs as elongated-blocky ataxial crystals (sub)perpendicular to both vein walls and contains crack-seal host-rock inclusions indicating that these extension veins repeatedly re-opened and sealed by near-lithostatic fluid-pressures, as recorded in the fluid inclusions. Bedding-normal veins still reflect the extensional stress regime during the latest stages of the Ardenne-Eifel basin development.

The presence of bedding-parallel quartz veins is the first evidence of a compressional stress regime. Bedding-parallel veins, mostly present at the interface between two lithologies and folded across the hinge zone without thickness variation, show a pronounced composite bedding-parallel fabric, consisting of bedding-parallel host-rock inclusion bands and bedding-perpendicular inclusion trails. Quartz crystals show a strong variability in grain size indicating brittle cataclasis during vein formation. They are affected by recrystallisation during progressive veining and subsequent deformation. These macro- and microscopic observations indicate bedding-parallel thrusting preceded the formation of folds and the regional development of cleavage. Microthermometry of fluid inclusions suggests that lithostatic to supralithostatic fluid pressures were responsible for veining. These bedding-parallel veins thus reflect a brittle deformation in a strong upper crust that occurred at larger differential stresses than during the previous bedding-normal veining event, but still low enough to allow the formation of extension veins.

Fluid redistribution thus occurs during transition between two stress regimes in a sedimentary basin which has been recognised in mesozonal ore deposits around the world. The tectonically induced transition from an extensional to a compressional stress regime is accompanied by the increase of pore-fluid pressure up to near- or supralithostatic. These high fluid-pressures are only possible under relatively low values of differential stresses, in compartmentalised high-pressure reservoirs and are thus easier to maintain during the tectonic inversion than during syntectonic deformation, as shear fractures will develop due to the increased differential stress.

Characterising brittle reactivation in basement: an example from the Lewisian Gneiss Complex, NW Scotland

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It is widely accepted that pre-existing ductile and brittle fabrics in continental lithosphere influence the orientation and spatial characteristics of subsequent deformation structures. By using quantitative techniques to describe geometric and spatial attributes it should be possible to determine whether these pre-existing weaknesses affect fracture network development.
To test this hypothesis, the mainland Lewisian Gneiss Complex (LGC) is being used as a case study. The Late Archaean - Early Proterozoic LGC comprises several terranes of TTG gneisses; mafic and ultramafic dykes together with subordinate supracrustal sequences, with numerous ductile shear zones of variable width and metamorphic grade. Three main regional fracture sets are recognised (from oldest to youngest): (1) steeply-dipping NW-SE Paleoproterozoic faults that are preferentially developed as foliation-parallel structures in pre-existing ductile shear zones; (2) N-S to ENE-WSW trending hematite stained normal fault 'ladder fractures' associated with the deposition of the overlying Neoproterozoic (1.2 Ga.) Stoer Group sediments; (3) NE-SW-trending younger (Mesozoic?) faults and fractures??. Some of the older faults are locally reactivated during other regionally significant deformation episodes that affect NW Scotland, notably during the Silurian development of the Caledonian Moine Thrust Zone. Each fault set is associated with characteristic fault rock and mineral assemblages.
The present project focuses on characterising these fracture sets from regional to outcrop scale using a range of remote and fieldwork analysis techniques. Regional data comprises 2D lineament maps created from high resolution NEXTMap® digital elevation models. Outcrop data consists of 1D sample lines and 2D photo-mosaics which have allowed fracture attribute characterisations to be made. This study centres on the Assynt and Rhiconich terranes to assess the heterogeneity in fracture networks due to variations in lithology and metamorphic grade.
Results from statistical analysis of outcrop and regional orientation data show that outcrops in the granodioritic Assynt terrane exhibit a correlation between intense foliation and preferential development of fracture sets in greenschist-facies shear zones. This does not necessarily require direct reactivation of pre-existing fabrics, e.g. the Stoer Group 'ladder fractures' preferentially occur within shear zones even though they cut across the foliation. These correlations do not apply in the granitic Rhiconich terrane, where it is apparent that fractures do not reactivate pre-existing fabrics and instead cut across the foliation, even within pre-existing (amphibolite facies) shear zones.
In conclusion, the heterogeneity of the fracture sets within the mainland LGC can be attributed to variations in lithology, metamorphic grade and pre-existing ductile and brittle basement structure, particulary in relation to phyllosilicates (greenschist facies) in shear zones which give a strong anisotropy, localising or impeding deformation depending on the orientation of the principal stress/strain axes.

Palaeostress reconstruction in the Lufilian Arc and the Kundulungu foreland (Katanga, Democratic Republic of Congo): in search of evidence of incipient active rifting

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To the southwest of the central branch of the East-African rift system in the Lake Tanganyika region, morphotectonic evidence (e.g. Lake Mweru), shows seismicity and geothermal activity which indicates incipient active rifting. Our research focused on the brittle deformation structures that can be found in the Neoproterozoic Katangan sedimentary series in the Lufilian Arc and its foreland. These sedimentary series, typically known for their high-grade host copper-cobalt ores, were folded, brecciated and faulted during the Pan-African orogeny (ranging from 560 to 520 Ma). By performing a regional paleostress reconstruction, we intend to determine whether or not the Lufilian Arc is already affected by incipient active rifting and whether or not this has caused any remobilization of the Cu-Co ores.
Fault-slip data have been sampled in open pit mines and occasional outcrops at different sites across the Lufilian Arc and its foreland. We apply a paleostress reconstruction using the Tensor software based on both fault kinematics and field observations in order to comprehend fracture types and their chronology as well as fault behaviour and associated mineralization.
Our interpretation suggests successive brittle tectonic stages with particular stress states postdating the main stage of the Neoproterozoic Pan-African orogeny. For the early fracturing stages, varying stress magnitude and orientation is evidenced. This early brittle compression event is interpreted as syn-orogenic. It can be correlated across all the mine locations in the Arc and predates the Cu-Co remobilization. The cross-cutting relationship and fracture chronology indicate a certain multiphase development of the Cu-sulphide mineralization. We show that this multiphase mineralization is linked to polyphase strike-slip and extension faulting, rather than to compression. Dip-slip sub-vertical faults are typically found in the central part of the Arc. They are sometimes mineralized and mainly reactivate bedding planes.
They occur in both limbs of the major fold structures, as well as within the tectonic breccia that commonly occupy the core of the folds, both suggesting a post-folding brittle extension faulting event. The significance of these brittle structures is discussed in terms of possible, syn-orogenic extension and vertical extrusion, late-orogenic collapse, post-orogenic foreland compression reactivation or later rift-related extension.
The brittle structural data set records different stress solutions of regional importance, leading to a subdivision of the Lufilian Arc into zones of different fracturing behaviour. The southeastern part is dominated by strike-slip and extension stress regimes with significant bedding-parallel normal slip movement; the central part mainly recorded a compression regime, typically with dip-slip vertical faults; the foreland is successively characterized by compression and extension regimes. All these fracturing events successively reflect the Pan-African orogeny, a later compression event of possible Late Paleozoic-Early Mesozoic age, followed by extension. The youngest brittle structure generation complies with a stress field reconstruction that is compatible with recent local earthquake focal mechanisms.

The origin and evolution of the Cretaceous northwest Sirt Basin, Libya, based on remote sensing interpretation and well data analysis

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The Cretaceous-Tertiary northwest-trending Sirt Basin system, Libya is a rift/sag basin formed on Pan-African- to Paleozoic-aged basement of North Africa. In this study, we aim to investigate the rift-basin architecture and tectonic framework of the western portion of the Sirt Basin covering an area of approximately 180,000 km^2. Remote sensing data and geophysical data supported by borehole data from about 300 deep wells and surface geologic maps where used to construct geological cross sections and surface geology maps. Most of the oil fields which are present in the study area appear to be associated with structural hinge zones and adjoining highs.

Late Eocene rocks exposed at the surface in the western part of the basin contain a complex network of branching normal and strike-slip faults, generally with a NNW-SSE structural grain. Many surface structural features have been interpreted from satellite images which confirm sinistral strike-slip kinematics. For example, a set of splay faults at the north of the Jedari fault form a well-defined horsetail structure. Relay ramp structures, and open fold structures appear in the area to be parallel to the main NNW-SSE tectonic trend. By integrating remote sensing and seismic data, we have identified roll-over anticlines, horst/grabens and negative and positive flower structures. These structural patterns reflect the Cretaceous/Tertiary extensional tectonics and possibly also control by an underlying pre-existing Pan-African basement fabric and ENE-WSW trending Hercynian structures.

The age of rifting and the subsidence rate within the study area is constrained by two deep wells, one on a platform and the other in an adjacent trough. They show that there are variations in thickness and subsidence that suggest several important pulses in tectonic activity, corresponding to an initial Early Cretaceous rifting event which peaked in the Late Cretaceous, and a subsequent Paleocene–Eocene sag phase. In general, sediments of Mesozoic rocks show stronger lateral and vertical variations in thickness and lithology than those of overlying Tertiary sediments. This allowed us to define pre-rift, syn-rift and post-rift sediments of the Western Sirt basin. Fault reactivation has been recognized by differences in thickness of Paleocene (Satal carbonates) and Early Eocene times (Hon evaporites) compared with other stratigraphic units.

Our study has revealed that the overall tectonic setting of the area is controlled by northwest-southeast-trending faults that may have formed as early as Early Paleozoic times. Ongoing work (fieldwork, seismic interpretation and potential field modeling) is seeking to to establish the role of oblique tectonics basement inheritance, and further constrain the Cretaceous tectonic framework.

InSAR mapping of an active Iranian salt extrusion

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Interferometric synthetic aperture radar (InSAR) imaging is a powerful technique which is increasingly used to extract detailed three dimensional information on Earth surface structures, including exposed diapiric surfaces. We have used InSAR to map, for the first time, the cumulative surface deformation in a 6×6 km region surrounding an active salt diapir (Syahoo) and its associated surface salt flow (or namakier) exposed in the Zagros Mountains of southern Iran. Images provided by the European Space Agency (ESA) were acquired in 12 increments over a 14 year interval between July 1992 and May 2006. The displacement of salt is non-steady and varies between surficial uplifts of +511 mm to subsidence of -803 mm per year. Growth of a central topographic dome occurs during short wet intervals to create a salt fountain morphology, which then slowly decays during the intervening long dry periods. Salt associated with dynamic “bulging” of the central dome during wet intervals may flow laterally via gravity-spreading into the surrounding salt sheet, resulting in deflation and subsidence of the dome, which is counteracted by growth and inflation of the adjacent namakiers. Salt “bulges” which migrate down the namakier, resulting in local inflationary and deflationary cycles of the surface, may be regarded as episodic pulses of gravity spreading whereby the salt strives for dynamic equilibrium. As long as the source of salt remains undepleted, then gravity spreading of the dome ultimately results in more buoyancy-driven salt flowing up the diapiric neck to replenish and feed the extrusion and maintain the gross fountain morphology.

Reference

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DOI: 10.1144/0016-7649.2008-165

Geology of the Ordovician Tyrone Igneous Complex, Northern Ireland

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Within the British and Irish Caledonides, the Tyrone Igneous Complex (TIC) is the most extensive area of ophiolitic and arc-related rocks remaining along the northern palaeo-margin of Iapetus. In its broader Caledonian-Appalation content, the TIC correlates most closely with the Notre-Dame Subzone of the Dunnage Zone of Newfoundland, Canada.

This paper presents a synthesis of previous geological mapping and research combined with the more recent Tellus geophysical survey data and its interpretation, U-Pb geochronology and whole-rock geochemical analyses, the combination of which has significantly improved our understanding of the geological evolution of the complex.

These data demonstrate that the Tyrone Plutonic Group represents the uppermost portions of a supra-subduction zone ophiolite; with a U-Pb zircon age of 480 Ma ± 1 Ma constraining its formation. Field relationships and inherited zircon cores within the arc-related intrusive rocks indicate obduction onto the Tyrone Central Inlier occurred prior to 469.9 ± 2.9 Ma.

The Tyrone Volcanic Group represents an intra-oceanic arc which collided with the Laurentian Margin during the Grampian Orogeny. It displays evidence for cyclicity associated with rifting, and frequent replenishment of the underlying source region through the upwelling of undepleted asthenosphere of eMORB composition. Accretion of the Tyrone Volcanic Group occurred prior to ~465 Ma. A suite of U-Pb ages from arc-related intrusive rocks, which cut the complex, show two distinct groupings, with significantly higher LREE enrichment in the latter suite. Both intrusive phases represent separate episodes of subduction associated with arc-continent collision during the Grampian Orogeny.

Polyphase deformation in the Lake Hazen region, at 82^{o} north on Ellesmere Island: implications for the tectonic evolution of the High Arctic

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The Canadian Arctic Islands are a vast remote wilderness, much of which has only been mapped at a reconnaissance level by the Geological Survey of Canada. As a result, there is a paucity of detailed structural data for the region. Renewed interest in the potential geological resources of the Arctic has led to increasing scientific activity in the region in recent years. The data emerging from these studies are crucial to constraining models for the tectonic evolution of the region and will ultimately help us to understand the potential resources of the Arctic.

In summer 2009, geologists from CASP completed a 7 week expedition to Lake Hazen, situated at 82^{o} north in northeast Ellesmere Island. The focus of the fieldwork was to document the structure, stratigraphy, provenance and sedimentology of the rocks in the region. This work represents the most detailed study of this area to date. Preliminary results from this field season provide fresh insights into the tectonic evolution of the area and provide important constraints for tectonostratigraphic models of the Canadian Arctic during the Phanerozoic.

The geology of the Lake Hazen region includes Neoproterozoic and lower Palaeozoic meta-sediments of the Franklinian succession, late Palaeozoic to Cretaceous deposits of the Sverdrup succession, and latest Cretaceous to Paleogene deposits of the Lake Hazen Basin. Cretaceous dykes and sills associated with opening of the Arctic Ocean are also widespread in the region. Structural transects produced during the 2009 field season highlight a long polyphase deformation history in northeast Ellesmere Island, including ductile contractional structures produced during the late Devonian Ellesmerian Orogeny, extensional structures related to late Palaeozoic rifting and basin evolution, and brittle contractional structures formed during the Cenozoic Eurekan Orogeny.

CASPs fieldwork programme in the Canadian Arctic is part of an ongoing project to understand the timing, extent and cause of the Ellesmerian Orogeny in the late Devonian and early Carboniferous, the tectonostratigraphic evolution of the Sverdrup Basin in the late Palaeozoic and throughout the Mesozoic, and to constrain models for the opening of the Arctic Ocean in the Cretaceous.

A ruck, a ramp and imbricate stack, but no culmination – the Dundonnell sector of the Caledonian Moine Thrust Belt, Northwest Highlands of Scotland.

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The Dundonnell Culmination in the Moine Thrust Belt of NW Scotland has been interpreted as the type example of an antiformal-stack duplex in a fold-and-thrust belt (Elliot & Johnson 1980; Boyer & Elliot 1982; Butler & Matthews 2009). Much of this interpretation has been based on the primary Geological Survey of the region (Peach et al. 1907). These early geologists identified a WSW-ENE elongate antiformal structure formed in Neoproterozoic (Torridonian) and Cambro-Ordovician sedimentary strata immediately beneath the Moine Thrust. The Moine Thrust was shown to be deformed by this structure, thus providing evidence for the foreland-propagating nature of the thrust belt. The antiformal axis was shown to be aligned oblique to the trace of the Moine Thrust Belt, and to the (top-to-WNW) thrust transport direction.

Much less well known is that along strike from the culmination, the primary survey also identified an approximately 200 m wide linear belt of “generally contorted schist” in the Moine rocks structurally above the Dundonnell antiform. The 19th century survey field slips identify a WSW-ENE trending “RUCK”.

New geological mapping does not support an antiformal-stack duplex at Dundonnell. There is no folded repetition of the stratigraphy or lithology across the culmination; instead moderate to steep SSE-dips are observed right across the structure. On the south side of the structure, clastic rocks immediately beneath the Moine Thrust are intensely mylonitic; in contrast on the north side undeformed, massive sandstone dominates, within which there is little or no evidence for ductile deformation. We instead interpret the Dundonnell structure as a steeply-inclined imbricate stack, lacking antiformal upright folding. The imbricate stack bulges up and displaces both the ductile and brittle Moine Thrust.

The northern limit of the Dundonnell imbricate stack is defined by a brittle or brittle-ductile fault breaching the Moine Thrust; the Loch an Daimh Fault. This fault continues WNW and also defines the northern limit of the so-called ‘ruck’ in the Moine rocks. This ‘ruck’ is a transpressional flower structure positioned on a WSW-ENE trending oblique lateral ramp. We argue that the Dundonnell stack has been constructed on that same ramp. The Loch an Daimh Fault clearly displaces the Moine Thrust but does not displace the structurally lowest thrust plane at Dundonnell, instead it flattens and roots southwards into the brittle base of the thrust pile.

North of Dundonnel, the Ullapool Thrust Sheet comprises Archaean gneisses and Neoproterozoic sedimentary rocks; this thrust sheet terminates southwards at Dundonnell. We propose that the Dundonnell Stack, and the transpressional flower structure in the Moine rocks, are constrained by the oblique lateral ramp corresponding to the southern limit of this thrust sheet.

Evidence for Quaternary convergence between the North American and South American plates, east of the Lesser Antilles.

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New seismic and bathymetric data from the plate boundary zone between the North American and South American plates, east of the Caribbean, show evidence of N-S compressional deformation that has produced basement-uplift and folding and faulting of the sedimentary cover. The 220-km-wide zone contains the Barracuda and Tiburon ridges, which have been uplifted, tilting the older sediments that cover them. The base of a sequence of younger turbidite-dominated sediments that fills the basin between the two ridges and shows synsedimentary deformation is dated as latest Pliocene, from correlation with DSDP site 27. In the turbidite-filled trough north of the Barracuda Ridge, the crests of anticlines deform the seabed and the shallowest sediment layers thin or pinch out over them, demonstrating very recent activity. The greater part of the uplift of the Barracuda and Tiburon ridges appears to have occurred over the last 2 Ma.

Thermal weakening localizes intraplate deformation along the southern Australian continental margin

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The southern Australian continental margin has been undergoing mild active deformation over the past ~10 Myr, which is manifested today by unusually high levels of seismicity for a relatively stable intraplate region. However, this deformation is markedly partitioned, with zones of abundant neotectonic structures, enhanced relief and high seismicity like the Flinders Ranges and Southeastern Highlands separated by areas of little neotectonic activity, subdued topography and low levels of seismicity like the Murray and Eucla basins. We have made a new compilation of heat flow data for the southern margin comprising 192 measurements. This new database shows that variations in heat flow correlate well with the distribution of neotectonic structures and historical record of seismicity, with regions of active deformation corresponding to elevated heat flows of up to ~90 mWm^{-2}. We propose that the southern Australian margin provides the best example to-date that active intraplate deformation may be localized by the thermal properties of the crust and upper mantle.

Structural Controls on the Evolution of the Southeastern Brazilian Continental Margin

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The South Atlantic passive margins show considerable variation along strike in terms of both structural style and margin width. Much of this change is thought to be due to variations in basement structure. Previous studies have shown that the influence of pre-existing structures can range from metre-scale local variations in basement fabrics to tens of kilometre-scale lithospheric heterogeneities relating to past deformation events.

The Santos basin (offshore Rio de Janeiro, Brazil) is an increasingly important target for hydrocarbon exploration. The basin is thought to be underlain by thinned continental crust, possibly part of the Neoproterozoic Ribeira mobile belt, whose structures onshore lie parallel or sub-parallel to the continental margin. The formation of structures in the Santos basin and onshore southeastern Brazil has previously been thought to have been controlled by reactivation of these basement structures. Recent discoveries such as the giant Tupi oil field and recently drilled dry wells in the basin (Guaraní, Corcovado-2), highlight the importance of understanding the sub-salt structure in the basin.

A remote sensing- and field-based study of structures formed during Cretaceous and Tertiary rifting events was carried out. 2 generations of structures have been identified: ~120Ma Cretaceous alkaline dykes and associated faults; and ~60Ma Tertiary faults, showing silicified breccias associated with further alkaline magmatism. A strong northeast – southwest structural trend is identified from remote sensed imagery. At outcrop scale, sinistral-oblique and normal faults appear to have formed during the Cretaceous and Tertiary, and Cretaceous dykes show sinistral-oblique emplacement kinematics. These datasets are consistent with sinistral transtension during repeated phases of regional east-west extension. Basement fabrics often show strike parallel to the northeast-southwest trend of the brittle structures, but show a wide variation in dip angle.

The identification of Cretaceous faults and fractures has shown for the first time that the early rifting can be studied onshore, as well as offshore. This study has also highlighted that, whilst we see a consistent trend of the brittle structures on both regional and outcrop scales, the basement fabrics display a great deal more heterogeneity. Where the basement is not oriented parallel to the northeast-southwest regional trend of brittle structures, we do not see an influence on the trend or structural style of the brittle faults. This suggests that whilst the local reactivation of basement fabrics plays a role, the ultimate control on the formation of brittle structures was at a larger scale relating to initiation of the South Atlantic.

Detachment faults during continental breakup and beyond.

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The formation of detachment faults has long been a subject of debate, with discussion focusing on whether the detachments formed at low-angle, formed at steep angles but remained active after rotation to low angles or formed and were only active at angles greater than about 30°, and have been passively rotated to low angles. I present images of detachment faults at both rifted margins and at slow-spreading mid ocean ridges that suggest that some detachments were indeed active at low-angle, but that most appear to have rotated to low-angle in a rolling-hinge manner.

Other questions concern the longevity of detachment systems, and their lateral extent. At mid-ocean ridges, oceanic core complexes are the unroofed footwall of major detachment faults, but typically extend in the transport direction as far as they do laterally. This either requires that the detachment itself continues in the subsurface laterally away from the exposed core complex or that the detachments terminate laterally: the possibility of "magmatic soft linkage" is explored.

A final discussion centres on the controls on whether the footwall to the detachment is exhumed at the seafloor or covered by small rafted blocks. This seems to depend on a combination of the internal friction coefficient of the fault rocks and on the degree of flexure of the footwall as it is unloaded.

Cenozoic history of Britain and Ireland: Implications of modern dynamic support for the Paleocene underplating idea, and quantification of plate boundary drivers of Cenozoic structural inversion

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The hypothesis that large thicknesses of magma were emplaced within the crust beneath Britain and Ireland during the Paleocene was advanced 15 years ago in response to observations from igneous petrology and sedimentary basin modelling. Several aspects of the igneous underplating scenario remain to be explained. Why is the maximum apparent exhumation in the East Irish Sea, a depocentre? Major crustal structures influenced escape of melt in Ulster and the Hebrides, but what stopped the inferred magma reaching the surface further south, where there are similar crustal structures? Large amounts of underplating imply high mantle temperatures and upwelling flux during the Middle Paleocene; how can these be reconciled with the observations that dynamic support was limited during the Middle Paleocene and reached a maximum during the latest Paleocene?

The twin foundations of the igneous underplating idea are the petrological evidence that more melt was produced than is seen at the surface, and a requirement for widespread permanent uplift inferred from missing post-rift thermal subsidence. The petrological argument seems robust but it can only be applied with confidence in the vicinity of the igneous centres. Attempts to link the widespread permanent uplift to localized structural inversion rather than widespread underplating continue to be made. However, the low elastic strength of the region continues to make it difficult to appeal to localized shortening to explain widespread permanent uplift.

These problems would be reduced if not all of the missing post-rift thermal subsidence need be attributed to permanent uplift. The shallow depths of oceanic lithosphere nearby to the west and the positive long wavelength gravity field (or equivalently geoid) over the British Isles itself indicate that the region is presently dynamically supported by several hundred metres on the edge of the modern Iceland plume swell. Simple calculations and modelling of backstripped subsidence histories show that the requirement for permanent uplift is significantly reduced when this factor is taken into account. The corresponding estimates of igneous underplating and of exhumation are also reduced. Exhumation estimates are further reduced when Early Cretaceous erosion is accounted for. This exercise improves the sediment mass balance between the Irish Sea region and sediment sinks offshore to the south-west.

What caused the Cenozoic structural inversion? Inversion structures also occur on the Greenland and Canadian margins. Alpine events could not have transmitted stress across the Mid Atlantic Ridge, so it seems more sensible to look for changes in the plate boundary surrounding Greenland. There is excellent evidence for a sudden change in spreading obliquity of 30˚ at the Reykjanes Ridge between chrons 18 and 17 (Late Eocene). A decrease of 13% in ridge push would have resulted; could this decrease have permitted northward- and westward-directed structural inversion of suitably oriented structures around Britain and Ireland during the Late Eocene and Early Oligocene? The direction and rate of spreading at the Reykjanes Ridge has remained constant since the Oligocene, but it might be possible to explain Miocene inversion structures by changes in ridge push owing to ridge elevation. There is good structural and seismic evidence that the mantle temperature beneath the Reykjanes Ridge increased by about 50 to 100˚C, as the head of the Iceland plume evolved. This change elevated the Reykjanes Ridge by 0.5 to 1 km and increased ridge push by 80 to 160% between the Early Oligocene and Middle Miocene.

Calculated petrophysical properties of rocks from CPO analysis by EBSD in a section across the Moho in Cabo Ortegal (N Spain)

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Rocks representing the transition between the upper mantle and the lower crust and exposed in continuity in the Upper Tectonic Unit of the Cabo Ortegal Complex (N Spain) were sampled for microstructural analysis. Crystallographic preferred orientation (CPO) in rock-forming minerals in selected samples was measured using EBSD to calculate the propagation velocities of seismic waves from elastic constants of mineral phases and their CPO patterns. When the cartographic arrangement of the rock units is considered, the velocity data highlights the reflectivity of two of the contacts, one representing a 'geophysical' Moho between eclogites and gneisses, the other the 'petrological' Moho, between mantle websterites and high pressure granulites of the lower crust. The study of the microstructure shows that the location of the second reflector is determined by the progress of the plagioclase-in reaction during high-pressure granulitization of the garnet-clinopyroxene rocks that form the lower crust. The appearance of plagioclase in these rocks reduces significantly seismic velocities, to well below 7.6 km/s. The migration of the reaction front through the lithostratigraphy during the progress of the reaction would have the effect of migrating a seismic reflector through the transition between the mantle and a mafic lower crust without major movement of a petrological contact.

Linking sill morphology to emplacement mechanisms

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We present field evidence from sheet intrusions in South Africa, USA and the UK showing that in certain situations, dependant on host rock lithology, the propagation of magma through normal brittle fracture can break down. In this circumstance a prevalent fluid/fluid or fluid/ductile relationship between host rock and intruding magma is often developed. Once this occurs, the evolution of a given sheet intrusion becomes distinctly different from that produced by normal brittle fracture alone. The break down in brittle fracture often leads to the development of magma fingers, which accelerate ahead of the main sheet of magma. It is important to note that it is ultimately the host rock lithology, and its coupled response to intrusion of magma which dictates the ongoing evolution of the morphology sheet intrusion.
Within the Golden Valley Sill, South Africa, an elliptical saucer-shaped sill 19 × 10 km in size, finger structures, 10's – 100'ms in scale occur on a widespread basis, over approx. a 45 km circumference of the outer sill. To trigger the formation of fingers over such a large area requires an equally large scale mechanism to exist. We propose that rapid fluidisation of host rock (leading to a fluid/fluid interface between host rock and magma) is caused by rapid un-confinement of heated pore fluids caused by the failure of roof rock during the transition from horizontal emplacement to inclined emplacement through host strata, causing brittle fracture to break down, at least for an instant.
In the Raton Basin, USA, intrusion of magma into high-ranked coal horizons has caused the coal to act in a fluid like fashion. This occurred cotempreounsly with the propagation of the magma. This led to the widespread development of elongate magma fingers across the basin, which have propagated through the coals in a ductile manner.

In each of the above cases normal brittle fracture has broken down as a result of a coupled response of host rock to intrusion of magma. To assess the situation in which ductile behaviour breaks down is difficult, however ductile behaviour will be most prevalent in sheet intrusions emplaced at paleo-depth of ~ < 2km, below this depth, the effects of compaction, expulsion of pore fluids and cementation will all act to inhibit a ductile response in host rocks, and predominantly a brittle regime will dominate (up to the brittle/ductile transition). As many laterally extensive sill and saucer-shaped sill complexes emplaced both offshore and onshore occur at Paleo-depths under a 2km depth range, e.g. Faroe-Shetland Basin, N.E Rockall trough, Karoo Basin, the effects of intruding magma on host rock properties cannot be ignored.

Cone sheet emplacement in sub-volcanic systems: a case study from Ardnamurchan, NW Scotland

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Inclined concentric sheet intrusions (ring dykes and cone sheets) are key elements of the intrusive framework of sub-volcanic systems (central complexes). The nucleus of volcanic centres are often identified by the focus of inward dipping cone sheets based on a fundamental assumption about how the general geometry and disposition of the sheets relates to a (central) source. We aim to test the implications for magmatic plumbing (magma flow and linkage) that is generated by this model and thereby examine this fundamental assumption of sub-volcanic systems. Here we present preliminary evidence for magma flow and emplacement dynamics from the cone sheets of Ardnamurchan, NW Scotland, using anisotropy of magnetic susceptibility (AMS) measurements and structural field observations.

AMS data from over 100 oriented block samples from the Ardnamurchan cone sheets reveals magnetic lineations that are consistent with visible magma flow indicators, such as step and broken bridge axes. Flow directions vary from strike parallel to dip parallel and cannot be traced back in a simple way to a source. Field observations show host rock behaviour during cone sheet emplacement can be linked to lithology; magma fingers (ductile) occur in Palaeogene volcanic and volcaniclastic rocks, broken bridges (brittle-ductile) occur in Mesozoic sediments, and angular xenoliths (brittle) occur in Proterozoic psammites. In well exposed coastal sections, cone sheets intruding Mesozoic sediments are observed parallel to bedding, transgressing up the sedimentary sequence and may be described as transgressive sills. At Mingary Pier (NM 493 626) the transgression appears to be controlled by host rock fractures.

Given that there is little compositional variation between different cone sheets, the host rock lithology and structure needs to be considered before grouping them into separate geometric suites related to volcanic centres. Flow direction data does not support a centralised source model and in fact reveals a general NW-SE trend suggesting an alternative source.

Contrasting magnetic susceptibility fabrics on opposite fold limbs: cause and implications

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Within its classical outcrop area, situated below the Middle Devonian angular unconformity, the lower Ludlow Ronquières Formation (Anglo-Brabant Deformation Belt, Belgium), contains several horizons of carbonate nodules. The shape, orientation and occurrence of these nodules have hitherto been unexplained. All nodules are characterized by a long axis oriented subparallel to the cleavage/bedding intersection lineation. Moreover, nodule shape appears to change around major fold structures. Previously, an analysis of the anisotropy of magnetic susceptibility (AMS) showed quite comparable results: a maximum susceptibility axis (K1) parallel to the cleavage/bedding intersection lineation and a susceptibility ellipsoid that changes from prolate to slightly oblate in function of the angle between cleavage and bedding. Because of this similar behaviour, a detailed comparison was attempted between nodule shape and orientation on the one hand and AMS on the other hand. For the AMS analysis, we sampled individual fine-grained levels of distal turbidite sequences, directly below the nodule horizons, across an asymmetric, decameter-scale fold.

Contrary to all our earlier findings, the maximum susceptibility axis (K1) within the subhorizontal limb is not oriented parallel to the cleavage/bedding intersection lineation. Instead, K1 is oriented NNE-SSW, perpendicular to cleavage. By contrast, within the steeply dipping fold limb, K1 is oriented along the cleavage/bedding intersection lineation. It is tempting to attribute this change in magnetic fabric to a higher amount of shear strain within the subhorizontal limb. However, cleavage orientation remains at high angles to bedding, and there are no indications for a higher amount of strain within the subhorizontal limb.

A determination of ferromagnetic mineralogy, using a stepwise demagnetization of a three-axis remanent magnetization, shows the occurrence of additional high-remanence carriers in the subhorizontal limb that are absent within the steep limb. The fact that the degree of anisotropy shows a negative relationship with the amount of magnetisation, indicates that the additional mineral phases are not parallel to the existing anisotropies (cleavage, bedding). This is compatible with the orientation of K1, suggestive of a cleavage-perpendicular orientation of these additional mineral phases. Moreover, a qualitative relationship was found between the amount of magnetisation and a small amount of brownish to red discoloration that traverses the rock along cleavage planes and sharp bedding contacts.

On the basis of these findings, a tectonic cause for the peculiar magnetic fabric orientation within the subhorizontal fold limb can be rejected. Instead, this magnetic fabric orientation can be attributed to precipitation of ferromagnetic carriers within existing cleavage planes. This precipitation is likely due to alteration related to the overlying Middle Devonian.

Characterising the role of basin margin structure on finite strain patterns across a 'cleavage' front from the Variscides of southern Ireland.

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Anisotropy of magnetic susceptibility (AMS) measurements were carried out on 25 oriented samples of Upper Devonian-Old Red Sandstone from the Munster Basin, south west Ireland. This region lies at the northern boundary of the Rhenohercynian Zone of the European Variscides. Deformation of a thick (7 km +) Upper Devonian continental clastic sequence and overlying Carboniferous marine carbonate/clastic sequence at the end of the Carboniferous is thought to have consisted of an initial phase of layer parallel shortening, followed by folding, ongoing cleavage development and late stage accommodation thrusting.

Four distinct types of AMS fabric have been identified that define zones relating to the degree of tectonic deformation. The relationship of the K_{min} axes to bedding and/or cleavage indicates the relative degree of tectonic overprint. In order of increasing tectonic strain the fabric types are: 1) primary sedimentary fabrics (essentially zero tectonic strain), 2) early layer parallel shortening (LPS)-cleavage controlled fabrics, 3) incomplete tectonic overprint and 4) complete tectonic overprint fabrics. These fabric zones extend beyond the basin margin and record a northerly decrease in deformation intensity.

Of particular interest is the Coomnacronia Fault, which marks an abrupt change from steeply dipping axial planar cleavage to the south to variably dipping passively rotated cleavage to the north. This is reflected in the AMS data and interpreted as an important boundary structure to the basin. This fault acted as a structural boundary between the full penetrative cleavage event to the south and a relatively weak cleavage preserving early LPS to the north.

Fault stepping and drainage evolution in the Corinth basin rift, Greece.

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Determining the history of activity of faults where structural evidence is subdued and reconstructing the relative contributions to strain of multiple faults can be challenging over geological timescales. Yet to understand the tectonic evolution of extensional basins, both the history and partition of strain during faulting must be established. The evolution of the sequence of extensional faulting has previously been studied from well-exposed outcrops, from subsurface seismic data and by modelling. Many of these studies deal with the growth of fault length and the amalgamation of initially small faults by lateral propagation: the phenomenon of parallel fault stepping which we present here is less studied.

Fault systems in rapidly-extending rifts where extension is focused are commonly reconstructed as basinward, or hangingwall stepping, of normal faults. We reconstruct the faulting history of a sub-basin of the Gulf of Corinth, a young continental rift in Central Greece, by using drainage systems to determine the relative timing of fault activity. Both drainage planform and drainage profiles that includes incision, nick points and continuity across interior drainage basin, are used to elucidate the relative timing of fault activity.

These drainage features give evidence of tectonic block rotation from which we identify two styles of fault system evolution. With death of the fault system bounding one side of the basin, upper crustal scale faults have stepped basinwards into the hangingwall, slip rates on these minor faults resulted in changes to drainage planform. The opposing basin bounding fault is still active, and here faulting has stepped into the former footwall. The commencement of intrabasinal faults and footwall stepping of the crustal scale fault appears co-incident with a change in kinematics already observed in the main rift basin.

A geological investigation into fault weakening mechanisms revealed in deep drill core from the San Andreas Fault Observatory at Depth (SAFOD)

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Geophysical measurements of surface heat flow and stress orientations adjacent to major faults such as the San Andreas Fault in California imply that such faults have anomalously low frictional strengths (μ<<0.6). Yet despite over 30 years of research, no clear consensus exists over the importance and causes of such weakness. One important reason for this impasse is that the existing, predominantly geophysical approaches demonstrate good evidence for fault weakness, but are unable to resolve its cause. The recent collection drilling of a deep borehole (known as SAFOD) across the San Andreas Fault and sampling of core materials from the heart of the San Andreas Fault at 3.3 km depths now allows direct geological study of fault zone processes at depth

In the region of the SAFOD borehole, the San Andreas Fault (SAF) separates two very different geological terranes referred to here as the Salinian and Great Valley blocks (SB, GVB). The three sections of core preserve a diverse range of fault rocks and pass through two currently active creeping shear zones that have deformed the well bore casing. These coincide with a broader (100-200m) region of high strain fault rocks formed at some time in the geological past, but now currently inactive. Both the slipping segments and older high strain zone(s) are developed in the GVB located NE of the terrane boundary.

Microstructurally, lower strain domains in both the SB & GVB preserve clear evidence for classic upper crustal cataclastic brittle faulting processes and associated fluid flow. The GVB in particular shows clear geological evidence for both fluid pressure and differential stress cycling (variable modes of hydrofacture associated with faults) during seismicity. There is also some evidence in all minor faults for the operation of of solution-precipitation creep and the localised growth of smectitic phyllosilicates (illite-smectite, chlorite-smectite).

High strain domains are characterised by the pervasive development of foliated cataclasites and gouge. Most minor faults and gouge sections are characterised by the development of interconnected networks of smectitic phyllosilicate which prelimary experimental studies suggest exhibit anomalously low friction coefficients . The largest displacement, most smectite-rich gouges also preserve numerous rounded 'exotic' clasts of serpentinite. It is proposed that the widespread growth of smectititic phases during stress-induced solution-precipitation creep processes reflects the flushing of cataclastic fault rocks with Mg-rich fluids derived from interactions with nearby serpentinite bodies located either at depth or entrained within the fault zone.

The SAFOD core fault rocks highlight the fundamental role played by fluid-rock interactions in upper crustal fault zones. There is clear evidence for the development of high pore fluid pressures (hydrofracture development), reaction weakening (phyllosilicate growth following cataclasis) and geometric weakening due to the development of weak interconnected layers. There are very significant similarities between the fault rocks seen here and those preserved along other deeply exhumed weak fault elsewhere in the world.

K-white mica thermo-barometry, conodont colour alteration index and vitrinite reflection: methods to distinguish nappes in a complex diagenetic to low-grade metamorphic nappe pile

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The Western Carpathians, as the direct continuation of the Alpine arc underwent a complex tectono-metamorphic evolution during Alpine orogeny resulting in formation of a nappe pile built up by different subduction -related metamorphic rocks. The innermost part of the nappe-stack contains tectonostratigraphic units originated from the passive margin of the Mesozoic Neotethys Ocean and from the oceanic lithosphere itself. These thin-skinned nappes have been sheared off their pre-alpine basement. The Late Jurassic (152-155 Ma) age and thermobarometric data of the subduction-related blueschist facies metamorphism are well constrained (350-460°C at 7-12 kbar and 7 to 10 kbar at 300-350°C from another part) (Faryad 1995; Faryad & Henjes-Kunst 1997). However, low-grade metamorphism is also present in subduction-related tectono-sedimentary mélanges into which the high-pressure metamorphic slices were tectonically emplaced during exhumation. Metamorphic features of the various constituents of these mélanges may elucidate the physical conditions (pressure–temperature paths) of subduction, collision and subsequent cooling (exhumation) of the upper oceanic crust and related rocks of the accretionary prism.
During our work a diagenetic to low-grade metamorphic thin-skinned nappe-pile of the Rudabánya Hills (Inner Western Carpathians) were studied by structural geological, metamorphic petrological and geochronological methods in order to unravel its deformation history and nappe stacking. The main problem was how to distinguish different tectonic units presumably characterised by small differences in degree of metamorphism, because diagenetic sedimentary rocks and metasediments at an incipient stage of metamorphism usually do not contain facies- or zone-indicating mineral assemblages. Since only local equilibrium may be achieved in these systems, geothermobarometers used in higher grade rocks are useless because the lack of diagnostic minerals. The solution was the combined use of K-white mica thermo-barometrical methods (Kübler index, Árkai index, K-white mica b cell dimension data), which can approach the boundary of diagenesis and metamorphism, Conodont Colour Alteration Indices (CAI), vitrinite reflexion data (VR) and micro-structural investigation. As a result, two low-grade metamorphic nappes were separated, which were affected by three events of ductile deformation (D_1 layer-parallel foliation, D_2 folding with axial plane foliation and D_3 kink bands): Metamorphic petrological data suggest metamorphism at the transition between the high-temperature anchizone and epizone (300–350°C at 2-2.5 kbar and at 3.5 kbar for the other nappe) (Kövér et al 2009). The main detected metamorphic event with D_1-D_2 deformation phases took place in Early Cretaceous (137–117 Ma) on the basis of illite K-Ar age determinations. These units overlie non-metamorphosed and fractured units, indicating post-metamorphic nappe emplacement. The metamorphosed complexes (nappes) thrust upon non-metamorphosed ones at 87–94 Ma (Kövér et al 2009).
The metamorphism and deformation of these nappes are related to late Middle Jurassic–earliest Cretaceous subduction of the Neotethys Ocean. The retrograde sub-greenschist facies

metamorphism of the blueschists (Árkai et al 2003) is coeval with the prograde low-grade metamorphism of the investigated tectono-sedimentary mélange. Post-metamorphic deformation phases, including nappe emplacement seem to be coeval with mid-Cretaceous deformations of other Inner Western Carpathian units farther to the north. This deformation is probably related to the closure of the Penninic-Vahic Ocean.

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3D Pulsating flow and possible strain pattern in general shear zones

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Geological structures can be classified and approximated analytically using basic critical flow patterns (Ramberg, 1974; Ottino, 1989; Passchier, 1997, Weijermars, 1997). In homogeneous and steady state flow we can describe the kinematics of structures in terms of either velocity or displacement gradients. Applying these concepts to deformable rocks, we can study the progressive deformation and related deformation path pattern in 2D or simple 3D systems. In details, steady state flow patterns are critically dependent on flow parameters like the relative magnitude of the vorticity number (W_n), dilatancy parameter (A_n) and strain rate. Ramberg (1974) and McKenzie (1979) indicated that for vorticity value W_n >1 only pulsating strain paths should strictly occur suggesting that the parameter which discriminates between real and complex eigenvalues is W_n. We demonstrate using simple algebra analysis that the clear threshold between pulsating and non pulsating fields fixed for W_n>1 and valid for planar flow cannot be strictly defined in a 3D flow system. Specifically the threshold limit is not valid for triclinic flow. In 3D flows, one of the three eigenvalues is always real and gives rise to an exponential flow component coexisting with a pulsating pattern defined by the other two complex conjugate eigenvalues. Due to this mathematical property, the existence of a stable or pulsating pattern strongly depends on the relative dominance of the real eigenvector with respect to the complex ones. As consequence the pattern behaviours are not simply imposed by the kinematical vorticity number but are also determined by both the amount of strain accumulation and the extrusion component. It is also shown that similar complex flow can theoretically occur locally within shear zones and can sustain some few predictable hyperbolic strain paths. This imply that within proper rheological flow condition initial strengthening - weakening pattern related to the pulsating flow can evolve toward more stable fabric and in similar contest the conventional overprinting relationship could not always be successfully applied.

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Fault and fracture patterns in low porosity chalk

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Fault systems, developed within low porosity fine-grained chalks, can act both as conduits or barriers and therefore strongly influence fluid flow. This is relevant to the hydrocarbon industry since half of the world's petroleum reserves occur within faulted carbonate reservoirs and these same fields can be potential sites for carbon capture storage (CCS). We studied faults with displacements ranging from few mm up to 10 m, developed within low-porosity, fine-grained Upper Cretaceous chalk which is well exposed in the Flamborough Head area (UK). Detailed field-based structural observations and mesoscale data collection, integrated with laser scanner technology (LiDAR), were performed alongside micro scale thin section analysis.

Small (few cm) and large (m scale) displacement faults have been studied at two locations, Selwick Bay (SB) and Dykes End (DE), characterized by different protoliths. Fine-grained chalk beds, up to 50 cm thick, are interlayered with thin to absent marl horizons at SB and thick, up to a few cm, horizons at DE. At both localities, small displacement faults display flat-ramp-flat geometry which appears to be controlled by the lithology through the interlayered marl horizons. Evidence for fluid assisted processes (i. e. pressure solution at compressional jogs and hydraulic brecciation at dilational jogs) are found at SB. No evidence for fluid assisted faulting processes has been observed at DE where the clay from the interlayered marl horizons are smeared out in the fault planes.

Large displacement faults (> 20 m) at SB are characterised by up to 2 m thick fault cores made of fault breccias and intense veining. The damage zones, developed on either sides of the fault core, contain thick (up to 15 cm) veins displaying "blocky" textures overprinting thin veins. There is evidence for bedding surfaces and stylolites being reactivated as veins.

Large displacement faults (> 1m) observed at DE possess narrow (1-10 cm) but continuous fault cores characterised by a discrete slip surface developed within coarse to fine grained fault gouges. An up to 4 m wide damage zone of open to partially clay-filled fractures is present on either side of the fault core.

1-D and 2-D quantitative analysis of the fracture pattern across large displacement fault zones at SB and DE show high fracture density in the entire damage zone and low fracture density in the fault core. Fracture connectivity is high only in those segments of the damage zone that are closer to the fault core (1-2 m). The fault core itself and those portions of the damage zone that are located far from the fault core (2-6 m) have low fracture connectivity. This suggests that the damage zone of the fault core can be subdivided into an intensively connected damage zone directly surrounding the fault core and a weakly connected damage zone further away from the fault core.

We propose that fluid circulation and fluid assisted processes along small displacement faults at SB was facilitated at dilational and compressional jogs developed along ramp-flat-ramp geometries. Conversely, fluid circulation was inhibited at DE due to much of the clay being smeared out in the fault planes from the interlayered marl horizons. Fluid circulation along large displacement faults appears to be controlled by the geometry of the fault zone and degree of connectivity of the fracture patterns. High fracture density and high connectivity domains only appear close (1-2 m) to the fault core and this is where we expect most of the fluid circulation has occurred.

Spatial analysis, structural geology and mineral exploration

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An on-going need in mineral exploration and resource evaluation is to precisely match resource positions and shapes with the structural geology. Variography is the standard statistical modelling tool, using sample pair differences it is data hungry requiring pre-selected ranges and delivering smoothed outcomes. Variography lacks the fidelity required for critical comparison with structural data where a lode may be only a few metres wide and of complex geometry.

SpaDiS™ technology examines the structure of point data distributions, with established applications in the identification of cryptic trends and the measurement of strain in rocks. Variously termed Vector Analysis, Fry Analysis and Patterson Plots, we prefer the more generic description of Auto-Correlation. Like variography the method uses pairs of data and the variation in value of the pair, but unlike variography has no critical statistical functions. Distance and angular truth are maintained with each and every pair plotted from a common origin making the Translations Plot. Whilst not commonly viewed as being fractal mathematics, the Translation Plot assumes that all spatial relationships observed on the initial and potentially incomplete data map are multiply repeated in a fractal manner throughout and at all scales for which data are supplied. For n data points (such as deposit locations) there are $n^2 - n$ points on the Translations Plot, and the Hausdorff dimension D is typically 0.2 to 0.5 larger than that of the original map. In 2D the Translations Plot is four times the size of the original plan and has a rotational symmetry. The translations comprise all possible spatial relationships and are a template for the interpretation of the map. The Translations Plot can be analysed critically with SpaDiS™ software including rose diagrams, variance, distance ranges and angular range, Hausdorff dimension and the ability to distinguish Natural and Sampling Distributions.

Research into Auto-Correlation began with one of the authors conducting an ineffective (unpublished) experiment measuring strain in porphyritic granites of the Gran Paradiso massif, Italy during a PhD study. The applications of Auto-Correlation to the mineral industry were realized upon appreciating the limitations of variography. Initially all research was on hard copy (a kind of therapy), but subsequently using SpaDiS™ software, now in its fifth version. Research, development and commercialisation were and are funded by Vearncombe & Associates Pty Ltd. Assistance with the development and commercialisation of the software has come from government awards and tax breaks that are small but invaluable in an environment providing little support for SMEs. Whilst software sales and consultancy provide a cash flow, the significant commercial opportunity is in the identification and development of business opportunities.

This presentation is illustrated with examples from the Archaean Murchison Province, Western Australia with reference to Natural Distributions of both gold and copper mineralisation. Similarities and differences in the clustering, distribution trends and structural controls of gold and copper occurrences will be discussed. There will then be a 3D demonstration of SpaDiS™ analysing a Sampling Distribution from the resource drilling at Austin, an important new Cu-Zn-Ag-Au VMS discovery made by Silver Swan Group Ltd (ASX: SWN).

Geometric and fractal functions in SpaDiS™ overcome the problems of statistical rounding in variography and have been instrumental to advances in the areas of gold, base metal and kimberlite (diamond) exploration targeting, 3D resource modeling, contaminant distribution and environmental studies. SpaDiS™ is available for sale or consultancy services through Vearncombe & Associates Pty Ltd www.vearncombe.com

Reconciliation of contrasting theories for joint spacing in layered sequences

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Opening-mode fractures in mechanically layered materials, such as sedimentary rock sequences or laminates, are often best, or exclusively, developed in the more brittle layers. Fieldwork on joints in layered rocks and physical experiments on laminates have revealed that the fracture spacing scales with layer thickness. A wide variety of mechanisms for the origin of layer-confined opening-mode fractures and their scaling relation have been suggested. In the present study we exclusively focus on one of the most common mechanisms, namely fracturing due to an applied layer-parallel extension under constant layer normal stress. Experimental work has revealed that under these circumstances fracture spacing decreases approximately as the inverse of the applied layer-parallel extension by fractures forming in-between existing fractures, a process referred to as sequential infilling. Eventually no further infill fractures form, irrespective of any further increase in applied extension, a condition called fracture saturation.

The evolution of fracturing in single layers with welded and/or frictional interfaces under extension is often predicted using 1-D approximations which are centred on the transfer of tensile stress from the matrix to the layer by means of interfacial shear stresses, commonly referred to as shear lag models. If interfacial slip is allowed then in the limit, i.e. when the entire interface is sliding, these 1-D approximations predict that the maximum fracture spacing to layer thickness ratio at saturation is equal to the ratio of layer tensile strength to interface shear strength.

The above-described 1-D approximations, however, were criticised in the past: First, for welded interfaces they predict zero joint spacing at large strain, i.e. the joint spacing decreases with increasing strain ad infinitum. Second they cannot predict the details of the 2-D stress distribution within the fracture bound blocks because they are 1-D approximations for which certain assumptions in terms of stress variations have to be made. 2-D continuum models (e.g. FEM) consisting of fractured layers embedded in an elastic matrix, however, have revealed that at a fracture spacing to layer thickness ratio of ~1.0 a through-going central belt of layer-parallel compressive normal stress develops in-between the fractures. This compressive stress is interpreted to inhibit further fracture growth and is hence used as an explanation for joint saturation.

In order to test these contrasting theories for joint spacing and saturation in single layers we performed a suite of discontinuum numerical models which permit simulation of the growth of fractures and associated interfacial, or bedding parallel, slip. The models demonstrate that the validity and consequent applicability of the 1-D shear-lag models depends on the ratio of layer tensile strength to interface shear strength. High ratios (ca. >3.0 in our models) promote interfacial slip and yield results that, in terms of fracturing and interfacial slip evolution, provide an excellent fit to a 1-D shear lag model. At lower strength ratios, however, interfacial slip is suppressed and the heterogeneous 2-D stress distribution within fracture-bound blocks controls further fracture nucleation. Two mechanisms are identified that lead to fracture spacing not predicted by 1-D models: (i) Curved fractures adjacent to exiting straight fractures and (ii) infill fractures which propagate through fracture bound blocks even though the layer-parallel normal stress in the centre is compressive. Our models provide a rationale for the wide range of joint spacing observed in nature and clearly demonstrate that joint spacing is not an indicator of joint system maturity, e.g. saturation, as has been previously suggested.

3D numerical modelling of the evolution of fault zone internal structure

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Faults are often simplified as planar structures but are, in reality, zones that contain variably deformed rock volumes, ranging from intact fault bound lenses to fault rock (breccia, gouge). The generation of fault bound lenses can often be explained by one of two processes: (i) Tip-line bifurcation in which a fault surface propagates through the rock volume and splits into two surfaces that enclose intact volume. (ii) Asperity bifurcation in which slip along a non-planar fault surface leads to the formation of a new fault strand that removes the fault plane irregularity. The newly formed fault bound lenses become progressively fractured with increasing fault displacement to become fault rock. Existing models for the formation of new fault strands, lenses and fault rock are, however, conceptual. We use the 3D Distinct Element Method (DEM) which represents rock as an assembly of cemented spheres, to model the propagation of normal faults through mechanically layered sequences. Although the numerical models are simple (e.g. effects of fluids and crystal plasticity are not included) they reproduce the two basic modes of generating fault bound lenses and the formation of fault rock, and provide unique insights into the 3D evolution of fault zone internal structure.

Structural modelling of possible contaminant pathways below nuclear installations

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Dounreay Nuclear Power station is situated in northern Caithness, Scotland on complex normally faulted Devonian sedimentary rocks with a thin, intermittent cover of superficial deposits comprising predominantly glacial tills of varying provenance.

Bedrock structure, fracture patterns and the relationships between bedrock and the overlying superficial deposits can have a considerable impact on the transmissivity of any possible contaminants. An understanding of how the bedrock-superficial boundary and the nature of how fractures and faults influence and control the transport of fluids are of key concern. The principal aims of this work are to gain an understanding of the processes and controls on fluid flow pathways within such complex geological terrains, and develop methods of stochastatically evaluating likely contamination transport within the subsurface.

This work focuses on the near surface bedrock geology and superficial deposits. The near surface geology of the Dounreay site comprises cyclic sequences of lacustrine rocks; their cyclicity has enabled a reference stratigraphy to be created and correlated across the site. This stratigraphy, the coastal exposure and the extensive amount of borehole data available, provide a unique opportunity to construct and constrain a three-dimensional bedrock model; the interpretive element of which has been robustly test using structural restoration techniques.

In the bedrock of Dounreay, three principle fracture sets have been identified previously. The first set trends roughly parallel to the faults and may have formed during early stages of faulting. The second set trends perpendicular to the first and probably formed during the active stage of faulting. The final set of fractures is bedding parallel and, related to unloading. This set appears to have the strongest control on subsurface fluid flow across the site and distinctive iron staining on the fracture surfaces can be observed. Fracture indices and RQD values have been determined from borehole data and interpolated across the extent of the bedrock model. This shows a clear relationship between fracture intensity and depth, and also to different lacustrine facies, as well as the proximity to faults. These relationships can be utilized stochastically to investigate dominant fluid transport pathways and directions within the bedrock.

The weathered bedrock zone, and the nature of its relationship to the fresh bedrock and superficial deposits is critical, as this zone may act as the primary conduit for the flow of shallow groundwater and contaminants. Current geological interpretations of the superficial deposits are based on their genesis. Consequently, subdivisions based on the origin of the sediments do not relate directly to their fluid transmissivity, the bedrock model, or the nature of the weathered zone. Current and future work is aimed at modeling the nature of the superficial deposits and the weathered zone as a function of their fluid transmissivity. This will enable stochastic prediction of likely fluid transport pathways within them, and of the interaction between these near surface pathways and those within the unweathered bedrock.

The research will provide a framework from which likely contamination scenarios can be modelled, both in the well-constrained subsurface of Dounreay, and at other nuclear installations where the nature of the subsurface is less well constrained.

Strain analysis from point fabric patterns: A new objective method

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A simple technique is devised for obtaining finite strain estimates from deformed patterns of points possessing anti-clustered properties. As an alternative to the Fry approach where analysis is carried out in the deformed state, the new method performs a large number of trial de-strainings of the point pattern. For each de-strained dataset, statistical analysis is carried out to identify the assumed properties of the point fabric in the pre-deformation state, namely that the points come from an isotropic but non-Poisson distribution. This computer-based procedure usually produces a number of acceptable solutions to the strain analysis problem, and thereby delivers an assessment of the precision of the strain results. Testing of the method with both synthetic and real datasets suggests that a best estimate for the strain ellipse is one corresponding to the centre of gravity on the Elliott strain plot. The performance of the new method compares favourably with existing Fry-type methods

Length-throw relationships in an evaporite-detached extensional fault array: The Bremstein Fault Complex, offshore mid-Norway

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Recent research into the tectono-stratigraphic evolution of rift basins has mainly focused on areas where evaporites have not influenced rift development. The presence of a ductile evaporite unit serves to mechanically decouple sub-evaporite strata from cover strata. This influences fault array development in terms of fault initiation, propagation and linkage, which in turn influences syn-rift sedimentation. In this study we use 2D and 3D seismic data, constrained by well data, to examine the structural geology and Jurassic to Cretaceous evolution of the Bremstein Fault Complex (BFC), which delineates the eastern flank of the Halten Terrace, offshore Mid-Norway. Here, the structural style is influenced by the presence of two approximately 400 m thick Triassic (pre-rift) evaporite layers that are separated by an approximately 500 m thick unit of claystone.

Two dominant fault orientations are observed along the BFC: i) a NE-SW-striking, basement-involved, sub-evaporite fault system, thought to represent the reactivation of older Caledonian trends, and ii) a N-S-striking fault system, largely restricted to the post-evaporite succession. The N-S striking faults terminate downwards into the upper evaporite layer and are associated with low-amplitude salt rollers in their footwalls. The degree of linkage between the sub-evaporite and cover faults ranges from hard-linked, through soft-linked, to completely decoupled. The resultant tilting of the evaporite leads to gravitational collapse of the cover stratigraphy, creating a system of decoupled normal faults above the evaporite units. Hence, structural style in the cover is strongly controlled by topography created by the sub-evaporite fault array.

Length-throw statistics, measured using TrapTester™, help to constrain the development of the BFC. Some examples of hard-linked sub-evaporite faults (i.e. sub-evaporite faults that continue upward into the evaporite cover) have throw maxima at or below base salt level, while others have throw maxima within the evaporite cover section. This suggests that some hard-linked sub-evaporite faults initiated within the sub-evaporite section and propagated upward into the cover, while others initiated within the evaporite cover section and propagated downward into the sub-evaporite section. Cover faults show throw minima that typically coincide with strong kinks in the map-view trace of the fault. These throw minima are interpreted as representing palaeo-segment boundaries. Sub-evaporite faults appear to lack such segmentation, perhaps because they are typically older structures (Caledonian or Permo-Triassic) that were rejuvenated during the Upper Jurassic, and throw variations have either been smoothed out during fault evolution, or did not exist in the first place. When length-throw data from this study and published data from elsewhere in the Halten Terrace are compiled, there is a statistically significant difference in throw/length ratios between sub-evaporite and cover faults, with cover faults being relatively under-displaced. This may be because cover faults are forming in reaction to already-established sub-evaporite fault systems, so that cover faults lengthen rapidly to match the underlying sub-evaporite fault systems. There appears to be little difference between data from evaporite-detached faults in the Halten Terrace and Canyonlands, and published data from fault systems without evaporite detachment. We conclude that cover and sub-evaporite faults initiate as independent arrays, but begin to interact and link through the evaporite layer as they evolve. The growth and linkage of the fault array has important consequences in terms of erosion patterns, sediment pathways, and deposition within the Halten Terrace.

Geological and structural evolution of the Rosaria Mare intraplatform Basin and its tectonic implications (Adria/Apulia plate boundary, SE Italy)

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In the context of a research project focused on the solution of geological problems related to the Mesozoic kinematics of the Adria/Apulia plate boundary, here we present new data on the structural evolution of the Rosaria Mare intra-platform Basin area (R.M.i.B.). This basin developed within the Apulian Carbonate Platform domain (A.C.P.) during the Upper Cretaceous-Miocene, and represents a key structural feature to assess the kinematics of the Adria/Apulia plate boundary during early convergence between African and Eurasian plates (Schettino & Turco, 2009).

The main aim of this work is the formulation of a conceptual tectonic model of the central A.C.P. by integrating offshore seismic data with available onshore stratigraphic data. The current work was carried out by employing the following methodologies: i) stratigraphic analysis of onshore and offshore log data obtained from commercial deep exploration wells, ii) structural interpretation of offshore seismic reflection profiles, iii) geological mapping of Cretaceous-to-Miocene carbonate rocks cropping-out in the selected area, and iv) 3D modelling of both stratigraphic horizons and fault surfaces by using the TrapTester 6 software (Badley Geoscience Limited).

Onshore, a regional unconformity marked by bauxites deposits of Upper Cenomanian-Turonian age, highlights differential emersion within the A.C.P.. This differential emersion was followed by transgression of shallow water carbonatic facies during the Coniacian-Lower Campanian. Subsequently, a new tectonic phase, led to the drowning of the south-eastern sector of the A.C.P. within the studied area, as recorded by the R.M.i.B. (Campanian-Maastrichtian). Seismic reflection profiles carried-out across this basin and areas nearby, show a complex structural setting related to the Upper Cretaceous tectonic. Normal faults, folds and transpressional lineaments influenced the sedimentation of platform-to-basin carbonates and, furthermore, led to the disarticulation and instability of the A.C.P. margin. Seismic profiles interpretation, 3D reconstruction and other geological evidences, allow us to conceptualize the presence of a possible negative flower geometry, associated to a deep transcurrent fault, in correspondance of the R.M.i.B..

Based on the amount of throw calculated along the normal faults, the inferred master strike slip fault of the R.M.i.B. could have solved a total horizontal displacement in the order of about 10 Km. This conclusion is in agreement with previous published data. Post Late-Cretaceous strike-slip motion has been also documented for the Mattinata-Gondola fault, north of the study area (Argnani et al., 2009). In conclusion we link the tectonic assemblage of the R.M.i.B. and the Mattinata-Gondola faults to a wide zone of deformation related to the incipient Adria/Apulia continental transform plate boundary.

Argnani, A., Rovere, M., and Bonazzi, C., 2009. Tectonics of the Mattinata fault, offshore south Gargano (southern Adriatic Sea, Italy): Implications for active deformation and seismotectonics in the foreland of the Southern Apennines: *Geological Society of America Bulletin, v. 121(9/10), p.1421-1440.*

Schettino, A., Turco, E., 2009. Tectonic history of the western Thetys since the late Triassic. *Geological Society of America Bulletin (in press)*.

Linking fault geometry with wall-rock deformation: 3-D seismic investigation deepwater Niger Delta

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A dip-steered seismic volume has been used to guide a detailed interpretation of the geometry of thrust fault planes and wall-rock surfaces imaged in 3-D seismic data from the Joint Development Zone, deepwater Niger delta (JDZ). The Gaussian and maximum curvatures of the attribute-defined fault surfaces were then mapped.

Similarity is a form of “coherence” attribute that expresses how much seismic trace segments look alike. The maximum curvature of a surface defines the largest absolute curvature of the surface. Gaussian curvature is defined as the product of the two principal maximum and minimum curvatures (k_1 and k_2) respectively that represents lines of zero surface torsion. During translation of wall-rocks across a fault surface exhibiting a Gaussian curvature that is positive (“synclastic” e.g. hemisphere) or negative (“anticlastic” e.g. Pringle crisps), convergent/divergent particle motion paths will induce permanent strain, the nature and intensity of which will be dependent on the geomechanical properties of the rocks and the rate of change of Gaussian curvature in the fault transport direction. Down-plunge culminations and depressions are characteristic features of fault corrugations, providing changes in Gaussian curvature in the fault transport direction.

We present examples of the geometry and curvature maps of toe-thrust planes and wall-rock surfaces. Slices through seismic attribute volumes parallel to the fault planes in the wall-rocks and attribute cross plots show some relations between areas of intense fault surface curvature and wall-rock deformation.

Different interpretations of thrust trajectories and strain distribution in a fold-and-thrust belt

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Interpretation of geological and seismic data is often subjective and multiple interpretations of the same data are possible. This is especially true for thrust-and-fold belts where an array of models have been used in terms of fold and fault geometry, trajectories, linkage and strain distribution. End-member models for fault-fold relationships are, however, rarely met in nature; yet, the geosciences community tends to rely heavily on these models when constructing their structural interpretations. This is further enhanced by the tendency of the community to prefer publishing – and reading! – a single interpretation, the “right answer”, rather than to encourage scientists to explore different interpretations and their implications to the presented model(s).
This presentation explores an array of structural interpretations performed by a group of experts (structural geologists, seismic interpreters, geophysicists) of a single high-resolution seismic profile across a deep-water fold-and-thrust belt, offshore Nigeria. The results show that individual differences in interpreting the fault trajectories, folding style and strain distribution are quite significant, even with a high-quality, spatially coherent dataset. This in turn has an impact on the implied kinematic, structural and/or tectonic model(s). Similar differences exist with other types of data used in structural interpretation, including field data. The choice of the final model is, naturally, critical in many areas of industry, e.g. in oil reservoir modelling.
The uninterpreted seismic image and all the interpretation are downloadable on the Virtual Seismic Atlas (VSA) website at www.seismicatlas.org (type ‘Nigeria exercise’ in the search box).

2010 Poster abstracts

UNIVERSITY OF BIRMINGHAM

The Origin and Nature of Cenozoic Faulting in North East Ireland

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The Cenozoic tectonics of North West Europe is generally attributed to a combination of three major controls: Alpine compression, mantle plume-related uplift and North Atlantic opening. The relative influence of each is the subject of ongoing debate. North East Ireland hosts extensive exposures of Paleogene rocks of the North Atlantic Igneous Province and in combination with a number of high resolution geophysical data sets, provides a firm basis for considering the contribution of each factor. Evidence derived from analysis of the Tellus aeromagnetic dataset suggests that North East Ireland was subjected to N-S Alpine compression resulting in strike-slip faulting, which was punctuated by plume-related NE-SW to ENE-WNW extension. The latter is reflected in the considerable numbers of associated WNW-NW trending dykes which have been revealed by the aeromagnetic survey and are age constrained by cross-cutting relationships with stratigraphic units, intrusions or faults. Four distinct swarms show different amounts of lateral displacement across NE-SW trending sinistral strike-slip faults, attesting to the broadly overlapping periods of extension and faulting. Strike-slip faulting conforms to conjugate pairs of NE-trending sinistral and NNW-trending dextral faults, with displacements of up to 2.5km. Sinistral faults reactivate pre-existing Caledonian and Carboniferous structures, whilst dextral faults show no evidence of previous structure. NNW-trending dextral faults mapped from seismic data farther to the south in the Irish Sea are believed to be the lateral equivalent of onshore structures which extend into the Lough Neagh Basin. The latter is characterised by thick sequences of both Oligocene clays and earlier Palaeocene basalts, and appears to represent a pull-apart basin which is close to the intersection of major dextral and sinistral strike-slip faults. Evidence therefore indicates that, during the Cenozoic, North East Ireland was tectonically controlled by a background N-S Alpine compression which was periodically overwhelmed by well-defined phases of plume-related rifting and associated volcanic emplacement.

The impact of strain, bedding plane friction and overburden pressure on joint spacing

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In layered sequences, rock joints usually best develop within the more brittle layers and commonly display a regular spacing that scales with layer thickness. A variety of conceptual and mechanical models have been advanced to explain this relationship. A limitation of previous approaches, however, is that fracture initiation and associated bedding-parallel slip are not explicitly simulated; instead, fractures were predefined and interfaces were welded. To surmount this problem, we have modelled the formation and growth of joints in layered sequences by using the two-dimensional Distinct Element Method (DEM) as implemented in the Particle Flow Code (PFC-2D). In PFC-2D, rock is represented by an assemblage of circular particles that are bonded at particle-particle contacts, with failure occurring when either the tensile or shear strength of a bond is exceeded. Model materials with different rheological properties can be generated by calibrating the results of synthetic mechanical test procedures with those of real rocks. Our simple models of jointing comprise a central brittle layer with high Young's modulus, which is embedded in a low Young's modulus matrix. The interfaces between the layers (i.e. bedding planes) are defined by 'smooth joint' contacts, a modelling feature that eliminates interparticle bumpiness and associated interlocking friction. Consequently, this feature allows the user to assign macroscopic properties such as friction along layer interfaces in a controlled manner. Layer parallel extension is applied by assigning a velocity to particles at the lateral boundaries of the model while maintaining a constant vertical confining pressure. Models were extended until joint saturation was reached in the central layer. We thereby explored the impact of strain, bedding plane friction and overburden pressure on joint spacing. The modelling revealed that joint spacing decreases as strain, bedding plane friction and overburden pressure are increased. Contrary to a leading established model the spacing of joints is not a diagnostic feature of joint system saturation.

Influence of deep transverse fault zones on the prospectivity, geometry and spatial arrangement on some hydrocarbon-related structures, Zagros fold and thrust belt, northern Iraq

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The Zagros fold and thrust belt in northern Iraq is generating much interest in the hydrocarbon industry, with its super giant fields and calculated oil reserves of billions of barrels. To date, few advances in the relationships between deep fault zones and fold and thrust structures in the shallow sequence have been published. However, comparisons may be made with findings in the Iranian Zagros and other fold and thrust belts.

The Zagros fold and thrust belt in Iraq and Iran is dominated by NW–SE-trending folds. It also displays dramatic changes in deformation style and fold geometry along-strike. Speculated deep fault zones (striking ~NE-SW in Iraq) that do not appear to cut the surface may have been reactivated through the Phanerozoic. Their repeated reactivation may have had significant influence on the Mesozoic and Cenozoic crustal section. They may have significantly influenced along-strike variations in: source, reservoir and seal rock thicknesses and quality, trap-generating deformation and hydrocarbon prospectivity.

This study addresses whether the locations of deep fault zones can be inferred by the spatial organization of the folds and abrupt changes in the styles of Neogene shortening above. It focuses on the Erbil and Sulaimaniyah regions of Kurdistan, northern Iraq, where dramatic along-strike variations in surface folding can be observed. Some issues for the exploration of this major hydrocarbon province are raised.

More insight into deep transverse fault zones is required to model their effect on the Mesozoic and Cenozoic crustal section. Better understanding may guide and improve hydrocarbon exploration, and further elucidate along-strike variations in: the petroleum system, hydrocarbon prospectivity and fluid migration.

Analysis of structural lineaments and their relationship with paleotension fields responsable for the formation of cenozoic brittle structures, Espirito Santo State (SE Brazil)

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Recent neotectonics studies and geomorphological analysis proved, in Espirito Santo State, sudest Brazil, that this region was exposed to two Quaternary tectonics events - right shear E-W (Pleistocene-Holocene) and NW-SE extension (Holocene). Geologically, the studied area is grouped into three main units: a pre-cambrian basement in the western part, which is mainly composed by metamorphic rocks and proterozoic igneus plutonics rocks; sedimentary rocks belonging to Barreiras Formation (Cenozoic), with a considerable predominance in the north and with isolated sedimentary bodies in the southern part of the state, belonging to Tabuleiros Costeiros; Quaternary coastal deposits, in the eastern most part of the area, which belong to the coastal plain domain. In the region, one important proterozoic structural form – Faixa Colatina - is present and it was reactivated in Mesozoic-Cenozoic times, with NNW-SSE orientation.

The purpose of this work is to investigate the relationship between structural data as faut/slicks measured in the field with structural lineament analysis from DEM images extrated with automatic procedures.

The working methodology consisted in: i) collection of fault/slickes data in the Cenozoic covering and relative paleostress field analysis; ii) processing and analysis of structural lineament map, from the digital elevation model (SRTM) using 200m/px resolution, with automatic methodology realised with SID (a facility at Laboratory of Quantitative Geodynamics and Remote Sensing (GeoQute) of RomaTre University); iii) elaboration of 32 windroses spatially distributed in the studied area; iv)correlation between structural data and the direction of lineament domains and; v) preparation of a the tectonic model at the crustal scale of the area.

Stereograms of structural data show the predominance of a horizontal relative compressive direction in the NE and from NW to NNW directions (i.e perpendicular to the horizontal extension). The analysis of the structural lineaments map show a predominance of the lineaments in the NE and NW to NNW directions, the last forming e small counterclockwise angle to the Faixa Colatina. This confirms the correspondence between structural lineaments and fault data from the field. In this way, lineaments which represent the NW to NNW direction can relate to transtensional left shear and correspond to the left shear events in the field data. Lineaments which present NE direction are parallel to the compression direction found in the field data analysis. The model proposed present a compressional arching in the lower crust. This compression is responsabile in surface of the NE extension together with to left-lateral transtensions along Faixa Colatina.

3D modelling of ore deposits geometry in the Variscan basement of SE Sardinia (Italy).

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Structural study of the Baccu Locci mine shows that most of its known mixed sulfides and AsPy-Au deposits occur in different type of ore bodies localized inside a major Variscan shear zone. Analysis of the mineralizations and their hosting mylonitic rocks indicates that they post-dated shortening (D1, LD1) and extensional (D2 D3) stages of variscan deformation. D1 is a fold-and-thrust event characterized by low-angle thrusts, recumbent isoclinal folds and associated axial planar S_1 foliation, and is related to nappe-style deformation. All these structure are deformed by upright folds related to the late stage of shortening (LD_1). D_2 folded and/or reactivated the thrust-related structures and formed asymmetric overturned folds; they are cut by transpressive e/o normal faults (D_3). The mineralization by mixed sulfides and AsPy-Au occurred after a prolonged brittle-ductile deformation history; their emplacement has been influenced by preexisting LD_1, D_2 and D3 structures. Interestingly the mineralizations are related to two different geometries, which have been recognized during the building of the 3D model. The mixed sulfides mineralization (Fig. 1a) has been emplaced along the D1 foliations folded by LD1 folds, thus the ore body is localizes at the core of the antiforms (Fig, 1 a). The main AsPy-Au ore bodies (Fig. 1a-b) are associated to jogs extending up to 300 m along the strike of transpessive dextral faults. The 3D modelling shows that jogs are developed where the fault plane changes its attitude following the reverse limb of D2 overturned folds (Fig. 1b). The three-dimensional interpretation of geological maps and cross-sections have been used to reproduce the truthfully geometry of ore deposits, highlighting that the geometry of deposits are strongly conditioned by pre-existing structures.

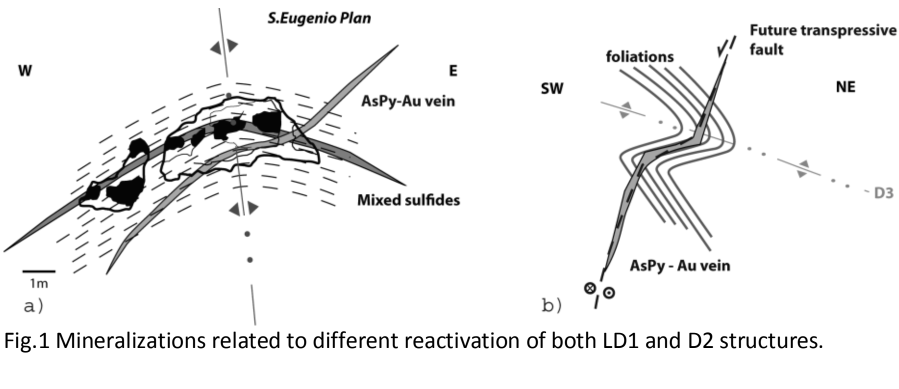

Fig.1 Mineralizations related to different reactivation of both LD1 and D2 structures.

Incorporating structural uncertainty into petroleum systems modelling to reduce exploration risk

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The modelling of faults and their effects on hydrocarbon migration, using techniques that evaluate juxtaposition and the development of fault-zone materials, has been a long-standing aspect of structural modelling within the hydrocarbons industry. Three-dimensional approaches to this analysis go some significant way to reducing inherent assumptions in the traditional two-dimensional approach. However, significant uncertainty in the outcome still exists by virtue of the fact that the initial structural model is an interpretation of limited and, in some instances, spatially inconsistent data, and therefore contains many uncertainties.

In this work we combine structural modelling with stratigraphy and hydrocarbon flow pathway modelling techniques to produce an integrated approach that allows uncertainty in structure to be addressed statistically and stochastically. Using this approach we are able to examine the important effects that uncertainty in various aspects of the structural model may have on the prediction of hydrocarbon accumulations and their potential volume. Specific structural uncertainties, such as the presence, absence or quanitity of fault-zone gouge, the permeability of juxtaposed stratigraphy and the propensity of faults to act as conduits to migration can be examined using multiple realisations of the same structural model and statistically comparing the outcomes. More general uncertainties, such as variation in fault displacement, variations in faulted stratigraphy, and sub seismic-scale structure associated with seismic-scale faults can be built into the modelling process and modelled stochastically. Together, these approaches highlight uncertainties in structure to which specific predicted hydrocarbon accumulations are sensitive, and, importantly, those uncertainties to which predicted accumulations are insensitive, thus reducing and clarifying exploration risk.

The methodology has been applied at a variety of scales from exploration play to prospect. In all cases, the controls that key uncertainties have on the location and volumes of predicted hydrocarbon accumulations are highlighted. Our results demonstrate that structural uncertainty can have a significant impact on the outcomes of petroleum systems modelling. Consequently, an analysis of structural uncertainty should form an integral part of the exploration workflow in order to both highlight and reduce exploration risk.

The Fluid Flow Evolution During the Seismic Cycle Within Overpressured Fault Zones in Evaporitic Sequences

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The integration of seismic reflection profiles with well-located earthquakes shows that the mainshocks of the 1997 Umbria-Marche seismic sequence ($M_w > 5$) nucleated at about 6 km depth, within the Triassic Evaporites, a 2 km thick sequence made of interbedded anhydrites and dolostones. Two boreholes, drilled northwest of the epicentral area, encountered CO_2 fluid overpressures at about 0.8 of the lithostatic load, at about 4 km depth. It has been proposed that the time-space evolution of the 1997 aftershock sequence, was driven by the coseismic release of trapped high-pressure fluids ($\lambda_v = 0.8$), within the Triassic Evaporites.
In order to understand whether CO_2 fluid overpressure can be maintained up to the coseismic period, and trigger earthquake nucleation, we modelled fluid flow through a mature fault zone within the Triassic Evaporites. We assume that fluid flow within the fault zone occurs in accord with the Darcy's Law. Under this condition, a near lithostatic pore pressure gradient can develop, within the fault zone, when the upward transport of fluid along the fault zone exceeds the fluid loss in a horizontal direction.
Our model's parameters are:
a) Fault zone structure: model inputs have been obtained from large fault zone analogues derived from field observation. The architecture of large fault zones within the TE is given by a distinct fault core, up to few meters thick, of very fine-grained fault rocks (cataclasites and fault gouge), where most of the shear strain has been accommodated, surrounded by a geometrically complex and heterogeneous damage zone (up to few tens of meters wide). The damage zone is characterized by adjacent zones of heavily fractured rocks (dolostones) and foliated rocks displaying little fracturing (anhydrites).
b) Fault zone permeability: field data suggests that the permeability of the fault core is relatively low due to the presence of fine grained fault rocks ($k < 10E\text{-}18\ m^2$). The permeability of the dolostones, within the damage zone, is likely to be high and controlled by mesoscale fracture patterns ($k > 10E\text{-}17\ m^2$). For the anhydrites, the permeability and porosity development was continuously measured prior and throughout triaxial loading tests, performed on borehole samples. The permeability of the anhydrites within the damage zone, due to the absence of mesoscale fracture patterns within Ca-sulphates layers, has been assumed to be as low as the values measured during our lab experiments ($k = 10E\text{-}17 – 10E\text{-}20\ m^2$).
Our model results show that, during the seismic cycle, the lateral fluid flux, across the fault zone, is always lower than the vertical parallel fluid flux. Under these conditions fluid overpressure within the fault zone can be sustained up to the coseismic period when earthquake nucleation occurs.
Our modelling shows that during extensional loading, overpressured fault zones within the Triassic Evaporites may develop and act as asperities, i.e. they are mechanically weaker than faults within the overlain carbonates at hydrostatic ($\lambda_V = 0.4$) pore fluid pressure conditions.

The Cantabrian Thrust Belt: basin history of the North Gondwana passive margin - rifting, glaciation? more rifting then collision.

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The Variscan thrust belt of the Cantabrian mountains in NW Spain preserves a Palaeozoic stratigraphy that developed during the evolution of the north Gondwana passive margin through multiple rift phases, drifting and eventual collision and collapse of the margin during the Variscan Orogeny. This Late Carboniferous collisional event generated a northward-vergent fold/thrust belt and coupled foreland basin system. Plate tectonic reconstructions show that the initial rifting that separated Avalonia from northern Gondwana commenced during the early Ordovician at polar latitudes and this gave rise to the Palaeozoic Rheic Ocean. Closure of the Rheic Ocean and collision occurred through the mid and late Carboniferous at equatorial latitudes.

The Somiedo-Correcillas (SCZ) and Bodón (BZ) thrust units in the provinces of León and Asturias exhibit largely un-metamorphosed stratigraphic sequences exposed in back-steepened, occasionally overturned, multiple thrust repetitions that show northward and north-eastward vergence. A striking feature of the Cantabrian belt is its curvature from an east-west trend in León Province in the south, through north south, to north northeast at the Asturias coastline of northern Spain. Before the opening of the Bay of Biscay in early Cretaceous times, the Cantabrian arc was continuous with the Variscan Armorican terrane.

The stratigraphy of the Gondwana passive margin generally comprises a sequence of carbonate and siliciclastic sediments with two significant hiatuses, one in the late Ordovician and early Silurian with a duration of some 40 Ma and a shorter one that took place prior to the deposition of Stephanian coal bearing sequences. In this integrated basin analysis project, palaeontological determinations have assisted in refining the chronostratigraphy and palaeobathymetric estimates have been made for the whole Palaeozoic sequence. The stratigraphy has been sub-divided into megasequences related to basin forming events with two pronounced rift events plus a thrust-related basin forming event. Using information on stratigraphic thickness, palaeontology, chronostratigraphy and palaeobathymetry, burial history curves clarify the details of basin evolution related to major tectonic events.

A NNE-SSW trending balanced cross section through the southern part of the Somiedo-Correcillas thrust unit shows the tectonic style, back steepening and northward vergence of the thrust system which exhibits horizontal shortening of some 60%+. The restored cross section does not show a simple layer-cake stratigraphy; rather it shows the presence of a pre-thrust geometry of horsts and grabens preserving condensed and expanded stratigraphic sequences in a rift basin template. Whilst evidence of Variscan contraction is abundant in small scale structures in the field, within the thrust sheets there are many minor rotated extensional faults, often conjugate that show a consistent stretching vector of NNE-SSW.

A broadly east-west correlation panel along the SCZ illustrates the detail of thickness changes within the syn-rift sequences and this coupled with the integrated geological database has been used as the basis for the construction of a chronostratigraphic diagram. Basin forming major faults, basin fill events and hiatuses are illustrated and these permit the development of an integrated and detailed basin history model for the northern Gondwana to Rheic Ocean passive margin in the Palaeozoic.

Structural evolution and fluid flow in the Wealden and Hampshire basins, southern England, U.K.

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From the Permian to the late Cenozoic southern England went through a complex structural evolution. A tensional stress regime during the Permian and Mesozoic produced a pattern of subsidence dominated by E-W striking normal faults. This tectonic regime was followed by a reversal of the subsidence pattern and inversion of the Wealden sedimentary basin in response to compressive tectonic stresses that converted the Mesozoic depocentres into structural highs during late Cretaceous and early Cenozoic times. Also during the Cenozoic the Hampshire basin formed as a direct result of crustal flexure. These events have produced a wide range of large- and small-scale structures that provide valuable record of structural evolution

The migration of petroleum and solute bearing fluids may have been controlled by the tectonic features such as faults. The timing and migration paths of these fluid movement events remain poorly constrained. Understanding the present day distribution of hydrocarbons and cements relies on understanding both the structure and fluid movement in these basins. The complex structural history of the Wealden and Hampshire basins provides an excellent opportunity to investigate links between structural evolution, petroleum migration and water movement.

Structures in outcrop and those displayed on published geological maps have been examined in order to determine the geometries, relative ages and stratigraphic ages of faults, veins systems and folds throughout the Wealden and Hampshire basins. Samples of cemented faults and veins have been collected from a wide range of stratigraphic units (Early Cretaceous to late Tertiary) in different structural positions. The faults and veins are concentrated in four locations, two on the Isle of Wight around the zones of flexure in Compton Bay and Culver Cliff, Cow Gap (Eastbourne) and Lydden spout (Dover). The veins are characterised by euhedral crystals attached to the veins walls, which indicates that the fills formed in an open cavity. Petrographical analysis indicates that these samples are dominantly calcite with minor amounts of pyrite and barite. The faults and veins in different orientations share the same mineralogy. The validity of this apparently simple pattern will be examined using fluid inclusion studies. By integrating these results with the chemistry of the source rocks and hydrocarbons found within the basins a model of fluid flow and the evolution will be established.

A geometrical relationship between imbricate thrust structures and their generated topography of mass-transport deposits (MTD's); implications for the accommodation of sediment laden gravity-driven flows.

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Thrust imbricate structures, frequently recognised in modern mass-transport deposits, culminate where compressional zones, caused by lateral and terminal confinement, are associated with ramping and emergence of the basal detachment. In cross-section they often stack in a consistent manner, forming repeatable thrust fault-fold geometries. In plan view they form characteristic pressure ridges that commonly appear arcuate and concave down-dip. A stack of imbricates therefore produces repeated sets of ridges forming individual quasi-isolated basins. These basins may act as traps for sediment or strongly control the pathway of gravity-driven flows that may form potential petroleum reservoirs. Thus, understanding of and being able to predict the basins' geometries requires knowledge of their formation.

A simple analytical model was developed to first approximate the magnitude of the topography, in terms of wavelength and amplitude, produced by 2 end-member fold mechanisms; fault-bend folding and fault-propagation folds, whilst varying their controlling parameters: (1) The amount of shortening; (2) the stratigraphic thickness of the imbricate; (3) the imbricate length; and (4) the fault angle.

Initial results were divided into two end-member states based on a wavelength to amplitude ratio (λ/A), which were plotted on a wavelength-amplitude matrix. It was seen that high λ/A were produced by low-angle faults with large imbricate lengths and low shortening amounts, thus producing a low undulating topography potentially yielding high degrees of connectivity and sediment bypass of gravity-driven flows between basins. High λ/A were produced by high-angle faults with low imbricate lengths and large thicknesses, thus producing a rough topography with isolated basins likely to result in local sediment ponding. Examples of these relationships between imbricate and topographic geometry are illustrated from shallow seismic analogues.

A layer cake model as a stratigraphic classification of mass-transport deposits (MTDs); from palaeo-flow directions and macro-scale structures, Paganzo basins, Argentina.

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Current classification systems of MTDs are based on longitudinal subdivision (i.e. head domain to the toe domain); reliant on identification of km-scale structures and kinematics or more complex process-oriented systems. These are mostly only applicable to seismic scale systems.
Presented is a stratigraphic classification comprising a layer cake model developed directly from 2 spectacularly exposed outcrops in Argentina. Using the type and presence of macro-scale structure (e.g. folds and faults), lithology (matrix and block composition) and palaeo-flow directions inferred from measured fold limbs 3 layers were identified: the ‘base’, the ‘filling’ and the ‘topping’. The base is characterised by decameter sized sandstone blocks plucked from the basal shear surface, boudinaged and then folded and sheared, comprising > 50% net to gross. The filling is characterised by near structureless siltstone with large decimeter rafts of protolith sediment, interpreted to have been passively translated in a ‘debrite-like’ flow. The topping is characterised by meter sized blocks and rafts, upright to inclined folds, thrusts and normal faults. Topography developed on the top surface, as determined by the internal structure controlled turbidite sedimentation.
Results from palaeo-flow directions indicate differing flow directions of each layer by c. 10%; these signify multi – direction flow of the MTD. We have therefore hypothesised that either the MTD developed as a single mass, each layer decoupling and behaving differently due to density and rheology contrasts, or that each layer resembles progressive temporal failure. Although this model is not mutually exclusive it is an example of horizontal stratification of large MTDs and internal multi-direction flow character.

Characterising fracture systems within upfaulted basement highs in the Hebridean Islands: an onshore analogue for the Clair Field

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The Clair oil field lies offshore from western Shetland and is estimated to contain over 4 billion bbl. The basement here is composed of Lewisian gneiss that is overlain by Devonian-Carboniferous sandstones and conglomerates and a Cretaceous seal. Reservoir performance indicates that fractured basement rocks play a significant role in the resource development of the Clair field. Consequently it is important to characterise and understand the fracture networks within the basement and, in so doing, determine a connected volume within the reservoir. Basement within the Clair field lies in the footwalls of major normal faults with Mesozoic age displacements whose characteristics are important to understand in order to gain a more accurate insight into fracture network behaviour.
Analysis will be undertaken on the nature and controls of fracture attributes across a range of scales in the crystalline Lewisian basement rocks, and in related Mesozoic cover sequences from Hebridean Islands that are exposed in uplifted footwalls of Mesozoic normal faults. This will enable characterisation of fractures and fracture networks as an analogue for the Clair field. An initial field study of the Stornoway Formation has yielded preliminary results of the structure of the formation and the contact between the Stornoway Formation and Lewisian gneiss basement on the Eye Peninsula.
Data will be used to build fracture networks at km to cm scales using lineament analysis of sources at scales from the regional to the microscopic. The resulting networks and attributes will then be compared both to equivalent fracture networks from the mainland Lewisian and from offshore areas based on interpretations of seismic reflection data and core materials from the Clair field. It will be determined to what extent scaling laws can be used to link across length scales and between 2D and 3D datasets.
The results of these studies will also lead to a new insight into the terranes of the Hebrides. Magnetic and Gravity anomaly maps will also be analysed in order further understand the terrane system and confirm whether the Hebridean Islands are an appropriate analogue of the Clair field.

Modelling continental margin extension using combined rigid/deformable plate tectonic reconstructions

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Plate tectonic reconstructions are essential for placing geological information in its correct spatial context, understanding depositional environments, defining basin dimensions and evolution, and serve as a basis for palaeogeographic mapping e.g. for palaeo-climate modelling. A well-known problem with traditional 'rigid' plate reconstructions is overlap and underfit of plates when restored in their pre-drift assemblages. This is attributed to internal deformation during (or after) continental break-up, calculation errors of finite poles of rotation within the global plate circuit (assuming rigid plates), and difficulties in resolving the position of the continent-ocean boundary at passive margins. To address these challenges, a new high-resolution palaeogeographic plate reconstruction model has been developed for the Mesozoic and Cenozoic that restores the extensional deformation produced at continental margins.

Continent-ocean boundaries (COB) have been redefined by utilising gradient changes in gravity anomalies, crustal thickness depth to Moho, differences in gravity signature over continental, transitional and oceanic crust, and the presence of extended fracture zones in oceanic crust.

The relative motions between major plates are determined by matching fractures and magnetic anomalies of similar age in oceanic basins. The relative plate motions of minor plates are calculated by Euler Pole addition in a global circuit, with central Africa at the uppermost position of the plate motion chain. For modelling extension on a global tectonic scale, beta factors have been calculated from the overlap of stretched conjugate passive margins over the relevant geological time span.

To remove the deformation effects produced by overlap in the reconstructions, an ArcMap™ extension has been developed (PLATE WIZARD™). This program creates displacement vector maps that allow restoration of the plate margins by 'warping' the mapped extended regions. The program also allows the restoration of the geometries of geo-referenced datasets that intersect with the plate margins defined by the model.

To date, a self-consistent global, plate tectonic model has been achieved, that incorporates stretching factors and scales deformation for the Cenozoic and Mesozoic. It is noted, however, that by resolving deformation geometries to pre-drift positions, the imprint of earlier rifting, strike slip and collisional histories are more clearly defined. This allows areas with a multi-phase tectonic history to be accurately modelled within a dynamic global framework.

Laccolithic emplacement of the Northern Arran Granite, Scotland: a new model based on Anisotropy of Magnetic Susceptibility

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AMS analysis was carried out on 43 oriented blocks from the Northern Arran Granite, which revealed a weak fabric. Mean susceptibilities average 3230 x 10^{-6} and range between 348 x 10^{-6} and 9000 x 10^{-6}, suggesting magnetite may be a significant AMS carrier. Anisotropies are up to 3.9 % and average 2.2 %, and are dominantly planar close to the margin where they dip steeply outwards. Magnetic lineations in most samples near to the margin are weak, except for samples near to the intersection of the Highland Boundary Fault (HBF), which are strongly linear. Samples in the centre of the pluton are more linear and subhorizontal or plunging gently SE. Samples which are more planar closer to the centre of the pluton are occasionally steeply inclined, these may represent boundaries between magma pulses, especially within the fine-grained inner granite.
The strongly asymmetric fabric pattern revealed by the AMS data does not support the previously proposed emplacement models which centre around a diapirc emplacement where country rocks are shouldered aside about a central focus. The data is consistent with NW directed forceful emplacement as a domed laccolith fed from an eastern region coincident with the HBF. The later 'fine grained inner granite' probably intruded as a series of sill-like sheets from the same feeder region.
Future work will attempt to reconcile the laccolithic emplacement with country rock structure and further constrain the AMS fabric and carriers with additional samples and magnetic measurements.

Consequences of Anisotropic Poroelasticity due to Fluid-Saturated Damage

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Patterns of microcrack damage in rocks within fault zones, subducting slabs and fractured reservoirs generate elastic anisotropy. In the presence of pore fluids, this elastically anisotropic damage can produce significant mechanical and seismological effects including: stress rotations in the cores of strike-slip and low-angle faults; trench-parallel fast axes of P and S waves in subducting slabs; and counter-intuitive changes to geomechanical risk in reservoirs undergoing injection or depletion. This contribution describes a theoretical basis for understanding these phenomena, explores the key sensitivities in the formulation and illustrates each case with simple models.
Previously published theoretical work has shown that the consequences of anisotropic poroelasticity critically depend on the Biot tensor. In isotropic porous rocks, this term collapses to a scalar and is often taken as unity, although the experimental evidence in support of this is scant. However, in damaged, anisotropic and fluid saturated rocks, the interaction of the Biot tensor with the pore fluid pressure term leads to significant changes in the effective stress, in comparison to the isotropic case. The Biot tensor is a function of the extrinsic – e.g. tectonic damage – and intrinsic – e.g. grain-scale fabric – elastic properties. Effective Medium Theory is used to predict the elastic properties of damaged rocks and to calculate values for the Biot tensor. The sensitivity of model predictions to variations in crack damage density, crack damage orientation and any original (intrinsic) fabric strength is explored.
The predicted changes in effective stress due to the combination of pore fluid pressure variations and anisotropic elastic properties have implications for the brittle failure of saturated rocks. The proximity to failure – shear failure, shear sliding or tensile failure – can be quantified. Comparisons are made between the proximity to failure of isotropic and anisotropic rocks.
There is a clear need for detailed field and microstructural studies to quantify the intensity and orientation of brittle damage patterns in fractured rocks, and to define any spatial variations within these patterns. These observations can then be integrated with the theoretical foundation described above to enhance our understanding of the mechanical response of fractured, saturated rock.

Structural analysis of fold and thrust structures from deepwater west Niger Delta.

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Deepwater fold-thrust belts are exceptionally well-imaged by seismic data. However, existing theoretical kinematic models of fold-thrust relationships generally do not provide adequate explanations of the data. A key omission in the models is the resence of significant distributed strains. Furthermore, relationships between the strain properties and seismic reflection character are poorly understood. In this presentation we examine part of the deepwater thrust belt of the west Niger Delta. Our study uses CGGVeritas 3D seismic data. Our analysis involves conventional interpretational workflows; picking the main reflector horizons, tracking fault traces and mapping of selected seismic attributes (e.g. coherency of amplitude along specific orientation). Different imaging and analytical workflows generate different predictions of thrust zone infrastructure and the geometry of the fold forelimbs. Reflector offsets along faults are plotted using displacement-distance diagrams and these in turn can provide estimates of strain distributed in the walls of the faults. These predictions are compared with seismic attributes to assess distributed strains in fold thrust structures. We discuss the implications for restoration workflows in these settings.

Application of dip-related seismic curvature attributes to map surface fault geometry: Examples from deepwater Niger Delta

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Seismic curvature describe the amount of bending in the seismic reflections and is geometrically the reciprocal of the radius of the local ellipsoid tangent to the seismic events. In two dimensions, positive curvature refers to antiformal features, negative refers to synformal features and zero curvature refers to planar features. In three dimensions, several measures of curvature can be extracted in the direction of the plane along which the measurement is made.
The seismic volume has been subject to several stages of post stack processing. A steering cube of the volume was first created. The steering volume contains the local dip and azimuth information of all seismic samples. The raw steering volume was further filtered to obtain large scale dip trends. The detailed steering volume was used to calculate the curvature attributes, while the background steering volume is the input together with the seismic to structure-oriented filters and subsequent similarity calculation.
The application of dip-steered volumetric seismic curvature attributes to 3-D seismic data has allowed the surface geometry of thrust faults to be recognized in the deep water Niger Delta. The attributes have been used to guide a detailed interpretation of the thrust faults in the area. The thrust faults are NW-SE trending in the first group and terminate against a second group of that is roughly E-W trending. Both groups are the result of gravity-driven compression of the thick deltaic sediments of Tertiary age.

Magma plumbing in the Judd Basin, North Atlantic, from opacity rendered 3D seismic data

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The Judd basin lies at the SW end of the Faroes-Shetland Basin, NE Atlantic, forming one of the marginal basins which fringe the outer edge of the basalts which dominate the area. The Judd basin contains only minor Palaeogene basalt flows in the north. In the south, transgressive, high impedance reflectors are interpreted as sills. In order to interpret the emplacement of the sill complex in terms of magma flow and linkages (i.e. magma plumbing) we have used opacity rendering to interpret the geometry and distribution of the sills. In the centre of the basin individual sills are saucer-shaped, except close to the Judd fault where fault planes and rotated fault blocks control final sill geometry. Several key intrusion structures that maybe used to infer magma flow (or sill propagation direction) have been identified. These structures include; bridges, broken bridges, steps and magma fingers. Magma fingers point in the direction of magma flow. Overlapping sill segments form a bridge of country rock. The axis of this bridge gives a flow/propagation azimuth. Further propagation and vertical thickening causes the bridge to break and the sills join in a step or broken bridge. Thus along strike progression from overlapping sills (bridge) to broken bridge or step indicates magma flow direction. Flow directions support centrally fed saucers and roughly radial flow pathways, where one particular lobe seems to be preferred as the feeder for the next sill. Sill linkage is normally achieved via relatively short conduits extending from tips of a cluster of magma fingers that then feeds the base or inner dish of the next sill. The pattern of sill linkage indicates that magma migrated from SW to NE. Our plumbing model suggests that an intersection of lineaments (possibly reactivated lower crustal faults) including the Judd fault system provided the access point into the crust for mantle derived magma. A lack of sills south of the Judd fault and basalts above it suggest that the Judd fault in the upper crust however acted as a boundary in the south, causing magma to migrate NE to the Faroes-Shetland area.

Fault-related fracturing in carbonate damage zones: field analysis and modeling from Central Apennines (Italy)

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The presence of "subseismic" fracturing and its connectivity rules the secondary permeability in carbonate rocks and therefore the pathway and the accumulation of deep fluids (water, hydrocarbon). The effects of fracturing are particularly evident in fault zones, where the damage-zone and the fault-core show different hydraulic properties. Typically, the damage zone is dominated by fracturing process that locally produces the increasing of permeability. On the other hand, the fault core is characterised by grinding process (comminution) resulting in a dramatic reduction of permeability across the fault (seal behaviour).
In this work we present the results of the structural fieldwork on 22 faults, performed in Meso-Cenozoic carbonate units of the Latium-Abruzzi Platform, Central Apennines, Italy. These units represent field analogues of rock reservoir in the Southern Apennines. Quantitative analyses of brittle deformation patterns i.e. pressure-solution surfaces, extensional fractures, and faults from field measurements, including bedding attitudes, fracturing type, attitude and spatial distribution (i.e. distance from the fault-core), were performed to better understand the architecture of normal fault damage zones.
To quantify the intensity of the brittle deformation we used the H/S ratio, where H is the fracture dimention on the normal plain created by the intersection between fracture plain and bedding plain and S is the spacing between two analogous fractures of the same set. The H/S ratio versus the distance from the fault core was analysed both in hangingwall and in the footwall of normal faults by using transect technique (DaisySoftware). The deformation intensity was measured also out to the damage-zones in order to compare the regional component of deformation to fault one. The analytical modeling of field data was carried by a Montecarlo-convergent method. It creates a large number of possible solution parameters and the resulting H/S values are compared with field data. For each item an error mean value is computed (RMS). Eventually, the method selects the set of parameters that produced the least value. The tested algorithm describes the expected H/S values as a function of the distance from the fault core (D), the clay content (S), and the fault throw (T). The preliminary results of this Montecarlo inversion show that the distance (D) is the most effective parameter in the H/S spatial distribution. The H/S value decreases with the increase of the distance from the fault-core. The rheological parameter shows a value similar to the diagenetic H/S values (1-1.5). The final equation has a RMS value of 0.116 with an H/S range between 1 and 12. The model is compared with a case of study to test the validity of the procedure.

How to Form a Rifted Margin – Fault, Fault and Fault Some More

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The structural evolution of continental crust at very high extensional strains, such as at Non-Volcanic Rifted Margins (West Iberian Margin) and margin basins (Rockall Trough and Porcupine Basin), cannot be fully described by accepted models of continental extension. Extension in the upper crust of these regions is apparently far less than the extension that is observed for the whole crust/lithosphere, creating an extension discrepancy. The three main hypotheses that attempt to account for the apparent extension discrepancy are; 1) depth-dependent stretching (DDS), 2) polyphase faulting, and 3) detachment faulting.
Here we present a fourth alternative - progressive polyphase faulting succeeded by development of serpentinite detachment faults. This model avoids volume conservation issues associated with convective thinning of the crust (DDS model), and provides a means of allowing large amounts of extension and thinning without major inferences on composition and rheological behaviour of the lower crust. Moreover it accounts for a significantly greater amount of extension minimising the apparent discrepancy.
Our model requires 3 stages of deformation during rifted margin development. These are 1) stretching, 2) thinning and 3) exhumation. The Porcupine Basin may demonstrate evidence for all 3 stages whilst the Rockall Trough may represent the transition from 2 to 3. The final stage is present on the West Iberian Margin.
Presented here are preliminary models for crustal strain accumulation following progressive polyphase faulting, in both mono- and di-polar (See-Saw) configurations. Future work will involve generating synthetic seismic sections for these models. This modelling will be further tuned using field data from the Betic Cordillera, SE Spain, where up to 20 km of thinning has occurred. Comparison between real and synthetic seismic data will allow better interpretation of extensional structures in the Porcupine Basin, Rockall Trough and W. Iberian Margin. Palinspastic restoration of seismic sections using MOVE will be incorporated to test validity of interpretations.

Examining the low-angle normal fault system of north-west Kea based on a new geological map

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The Aegean region, hosting the Western Cyclades and the island of Kea, are well known for and dominated by an extensional regime and fault zone formation. Low-angled fault geometries in the Northern and Eastern Cyclades are characterised by top-to-NNE directed movement and often associated with metamorphic core complex formation.
The geology of Kea is poorly known. Here we present a new tectono-/lithostratigraphic map of NW-Kea (Western Cyclades) revealing a hitherto undescribed major brittle-ductile low-angle normal fault, representing part of a domed crustal-scale normal fault system, formed during greenschist facies metamorphism. Within this fault system consistent top-to-S(S)W sense of shear was identified; this transport direction is in contrast to the NNE-kinematics within the Eastern Cyclades. Therefore a bi-directional extensional regime within the Aegean region is suggested.
Remapping the island a footwall and a fault-rock zone was distinct. The footwall is predominantly represented by greenschist-facies chlorite-epidote bearing schists intercalated with calcitic mylonitic marbles hosting thin quartz layers and quartzitic schists. Phyllonitic schists are observed around marble boudins and are thought to represent higher strain zones within the footwall unit. The fault-rock zone which comprises calcitic ultra-mylonitic marble and the HW-cataclasite associated with RMC (re-mobilised cataclasite) and strongly ankeritised dolomite. Brittle cohesive dolomitic cataclasites are separated by a strikingly sharp, but gently folded, fault surface from brittle-ductile dominated mylonitic marbles in the footwall.
Detailed structural investigations reveal a pervasive sub-horizontal foliation and upright folding. Due to a superposition of fold patterns some of which developed fold axis parallel to the overall stretching lineation, developing into sheath folds, indicating extensional high strain shearing. An early stage extension-related deformation phase involved ductile mylonitic processes dominating within the footwall and ductile/brittle cataclastic conditions associated with the calcite/dolomite dominated fault-rock zone. Samples record structures with a variety of transitions between the mylonitic and cataclastic end-members. In later exhumation multiple, low-angle cataclastic fault zones formed within, and (sub) parallel to a regional mylonitic ductile foliation, and a system of minor and major sets of high-angle sub-vertical cross-cutting steep faults, some of which acting as conduits for hydrothermal fluids evolved. We interpret these as indicators for co-genetic architecture and activity of both fault systems during the evolution of the normal fault system. Our data adds to the discussion on low-angle normal fault (dip <30°) development and geometry in areas of crustal extension.

Interactions between strike-slip faults, Westward Ho!: domino vs conjugate

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A network of strike-slip faults at Westward Ho (north Devon coast) has been investigated with the objective of determining their geometry, kinematics, fault interactions and mechanics, with particular reference to domino and conjugate systems. The strike-slip faults comprise NE-trending left-lateral faults and NW-trending right-lateral faults. They cut Upper Carboniferous sequences of repeated, coarsening-upwards cycles of mudstones, siltstones and sandstones, originally deposited in a deltaic environment. These cycles are divided into two formations: the Westward Ho! Formation (~400m) and the Bideford Group (~800m). The strike-slip faults cut steeply dipping beds, with WNW-trending Variscan folds being observed in the Bideford Group.

The strike-slip fault network at Westward Ho! has been accurately mapped in the field and multiple separation measurements made along each fault trace within the network. These data have been imported into ArcGIS, together with aerial photography. Techniques have been developed to map and extract fault separation data from the aerial photography. Multibeam bathymetry data for Barnstaple Bay area will also be integrated with these onshore data within ArcGIS.

It has been observed that the northern part of the study area (within the Westward Ho! Formation) is dominate by large (~30-50m) left-lateral faults with a spacing of ~100m. Between these, bedding is rotated clockwise and cut by smaller (~1-10m) antithetic right-lateral faults, forming a domino system. Farther south, in the Bideford Group, larger (~30m) right-lateral faults occur, which together with the large left-lateral faults form a conjugate system, with little overall rotation of bedding.

Variations in the displacement distribution of both domino and conjugate fault systems are compared using displacement:distance graphs and by plotting on the trace maps of the network. Discontinuities in displacement occur at fault intersections. In the domino-style faulting, antithetic faults account for more progressive changes in rotation and displacement along the major faults. Damage is localized at these fault intersections and in lenses produced along the main faults. In the conjugate-style systems major changes in displacement occur at the intersections of faults belonging to the two sets (left- and right-lateral) and larger damage zones are observed at these locations. Restorations of the fault movements (both displacement and rotation) illustrate the difference in overall strain in the conjugate and domino systems.

Thus, this investigation aims to help better understand of the kinematics of the ‘conjugate vs domino’ strike-slip system in this part of the Culm Basin and to determine the factors that control the style of faulting. This work forms part of a wider study aimed at understanding distribution and organization of displacement and damage within fault networks. The wider project objectives will be completed with reference to other field areas, and include: 1) the distribution of displacement and other attributes within fault networks; 2) the spatial and kinematic organization of conjugate fault systems; 3) the development and imaging of damage zones and the distribution of physical attributes around faults.

Quantification of Curvature and Fracture Distributions in Outcrop-Scale Periclines

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Fractures are important in understanding the permeability of rocks. They form in response to stresses accumulated within rocks. Numerical studies of both buckle and forced folds show that fold hinges focus stress leading to increased likelihood of fracture. When folding occurs above blind thrusts, hinge-parallel variation in displacement results in non-cylindrical (periclinal) folds with 3D strain fields quantifiable using curvature. In 3-dimensions, curvature is a tensor quantity with two extreme values (principle curvatures). The product of these curvatures, Gaussian curvature, highlights regions of extreme bending in more than one dimension and therefore accommodation of large non-plane strains.
We use terrestrial laser scanning to acquire a digital elevation model for three exemplar periclines, two from Scremerston, Northumberland and one from Bude, Cornwall which should show non-zero Gaussian curvature (Gaussian curvature is 0 for cylindrical or conical folds). The periclines are exposed single bedding surfaces allowing a full 3D survey of the surface. Colouring the point clouds using georeferenced digital photographs enables fracture traces to be picked from the surface of the folds. Principle curvatures are calculated from the smoothed, filtered point clouds. Fracture densities and trace orientations are calculated and these data plotted onto 3D surfaces derived from the triangulated point cloud data. This novel use of precisely georeferenced data allows the spatial variation of surface and fracture attributes to be examined and compared for entire folds with much higher resolution than previously possible.
Curvatures in excess of 0.1 m^{-1} are observed in one of the folds at Scremerston and correlate with increased fracture density around the hinge zone. Both of the other folds contain a significant amount of fracturing but neither shows a correlation between curvature and fracturing. The two folds at Scremerston show a pattern of minor domes and saddles imposed on the dominant fold. This is interpreted to result from minor undulations in the bedding surface prior to folding. The pericline at Bude shows very low Gaussian curvature ($<|0.01|m^{-2}$) indicating that the deformation producing the hinge parallel curvature is not distributed. Instead, it is interpreted to be accommodated by several large aperture fractures. This study shows that whilst curvature is a proxy for strain, it is not always a good proxy for fracture density – there is no systematic link. Many rocks have fracture densities inherited from early on in their strain history and the densities are not necessarily modified by folding. Structures which show whale-back geometries in the field do not always result from distributed, ductile strain. However, detailed investigation of appropriate field analogues provides limits to the values of fracturing and anisotropy that can be expected in the sub-surface.

The Sardic Phase.

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Before the Variscan Orogenesis, the oldest tectonic event which affected the Palaeozoic basement of Sardinia is the “so called” Sardic Phase, a deformation event generally recognized in the most of Variscan Terranes in the peri-Mediterranean areas. The study of the Sardic Phase would improve the knowledge about the tectonic evolution of Gondwana and surrounding areas before the Caledonian and Variscan events. In Sardinia the Sardic Phase was introduct by Stille in 1935 to account for the stratigraphical gap recognized in the Palaeozoic sequence between the Cambrian deposits and the Ordovician ones. The characteristic element of the Sardic Phase is the regional stratigraphic and angular unconformity, which in the Palaeozoic series of Sardinia separates the Cambro-Ordovician sequence from the underlying Middle-Upper Ordovician ones. This starts with trasgressive deposits, generally conglomeratic ones, in the External Zone (EZ) and in the External Nappe Zone (ENZ), and with vulcanites (ENZ).

In the Sardinian basement the Sardic Phase is well exposed in the SW of the Island where an angular unconformity cuts formations of Upper Tremadoc-Lower Cambrian of the pre-unconformity sequence, which is interested by different E-W structures, as like as metric to hettometric sized folds without cleavage , thrusts and thrust faults, related to the Sardic Phase. This stratigraphic gap is located between Arenig? and Caradoc.

Sedimentary breaks, as well as stratigraphic and/or angular unconformities, eventually with conglomerates or emersion deposits, folds, faults, several magmatic and volcanic of Ordovician age, related to the same time frame (Arenig?-Caradoc) of the Sardic Phase, were recognized in several regions: central-eastern Pyrenees, NW Spain, the Cantabric Zone, the Catalonian Coastal Range, the Iberian Cordillera, central-northern Portugal, the Montaigne Noire, the Mouthoumet Massif, the Armorican Massif and central-eastern Turkey. In the Eastern Pyrenees a succesion similar to the Palaeozoic sardinian one of the EZ is recognizable, where a pre-unconformity sequence interested by pre-variscan folds with the same characteristics of the sardic ones is separated from the post-unconformity sequence by a stratigraphic and angular unconformity (Casas et al., 2009). In the Catalonian Coastal Range a sequence similar to the sardinian one of the ENZ in Sardinia, is recognizable: a volcano-sedimentary sequence of Middle-Upper Ordovician age follows the unconformity (Barnolas & Garcia-Sansegundo, 1992).

Beside the main question (is the Sardic Phase a real tectonic phase?) several problems still remain unsolved: the correlation between different successions involved in the Sardic Phase in Iberia, Sardinia, Catalonian Coastal Range, Turkey, Mouthoumet Massif, Montagne Noire, Portugal; the occurrence and the meaning of the magmatic product related to the Sardic Phase.

The interpretation of major fault zone properties using three integrative approaches

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The Carboneras Fault Zone (CFZ) Almeria Province, SE Spain is an excellent example of a well preserved major strike-slip fault zone trending NE-SW, with several tens of kilometers displacement. Metamorphic basement and post-orogenic (Burdigalian-Messinian) sediments are exposed along a 15 km tract in the northeast of the zone; to the southwest the basement is buried by Plio-Quaternary sedimentary cover. The exceptional preservation in a semi-arid environment provides the opportunity to map the fault zone in detail. Fault rocks, formed at 3-6km depth throughout the Miocene period and exposed following uplift and erosion have been sampled for laboratory study.

The CFZ has developed in a basement terrain dominated by mica schist, giving rise to a braided network of foliated fault gouge. The width of the fault zone is several hundred meters, comprising individual strands of fault gouge a few meters thick. Bounding the fault zone, two main strands of clay-bearing fault rocks are enclosed by a tract of low-grade metamorphic andalusite-bearing schists. The geometry of the fault zone is constrained by the intrusion of andesitic rocks to the south and the period of orogenic activity (ending c. 25 Ma) marks the onset of fault movement. The lithological relations observed permit very detailed determination of the internal structure of the fault complex and the time sequence development.

The interpretation of the internal structure of the fault zone is based on (a) detailed geological mapping and (b) laboratory analysis comprising high pressure acoustic velocity measurements, optical and SEM microstructural study. Ultrasonic acoustic velocity measurements are made using standard equipment over confining and pore pressure ranges appropriate to the upper 10 km of the continental crust. We attempt to account for frequency-dependent effects using static elastic property determinations.

Seismic velocities can be approximated from modal analysis and mineral phase elastic properties, adjusted for the effects of porosity. Pore volumometry is essential for velocity determination on porous rocks so that any permanent damage due to application of effective pressure can be accounted for.

Density and velocity determinations from laboratory analysis and sections constructed from geological mapping will provide a '3D map', or representation of density and velocity throughout the CFZ from which it will be possible to compute seismic behaviour, i.e. forward (deterministic) modeling of the fault zone. In collaboration with the Universities of Liverpool and Granada, field seismic experiments (high resolution reflection and trapped wave studies) will be combined to produce a detailed understanding of the relations between structure and remotely sensed properties of the fault zone leading to the development of a three-dimensional synthetic velocity-density-stiffness model. Forward seismic modeling of the CFZ will allow for 'ground truth' comparisons with field seismic experiments.

The effects of crystallographic anisotropy on fracture development and acoustic emission in quartz

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Transgranular microcracking is fundamental for the initiation and propagation of all fractures in rocks. The geometry of these microcracks is primarily controlled by the interaction of the imposed stress field with the mineral elastic properties. However, the effects of anisotropic elastic properties of minerals on brittle fracture are not well understood. This study examines the effects of elastic anisotropy of quartz on the geometry of brittle fracture and related acoustic emissions (AE) developed during indentation experiments on single crystals at ambient pressure and temperature. A Hertzian cone crack developed during blunt indentation of a single crystal of flawless Brazilian quartz parallel to the c-axis shows geometric deviation away from predictions based on the isotropic case, consistent with trigonal symmetry. The visible cone crack penetration depth varies from 3 to 5 mm and apical angle from 53° to 40°. EBSD mapping of the crack tip shows fracturing initiates along a ~40 µm wide process zone comprising damage along overlapping en-echelon high-index crystallographic planes, shown by discrete bands of reduced EBSP quality (band contrast). Coalescence of these surfaces results in a stepped fracture morphology. Monitoring of AE during indentation reveals that the elastic anisotropy of quartz has a significant effect on AE relocation and focal mechanisms. 94 AE events were recorded during indentation and display an approximately linear relationship with loading and time. They correspond to the development of subsidiary concentric cracks peripheral to the main cone crack. The strong and complex anisotropy in seismic velocity (~28% V_p, ~43% V_s with trigonal symmetry) resulted in inaccurate AE relocation via the absolute (Geiger) relocation routine. This problem was overcome by using a relative (master event) algorithm that does not require *a priori* knowledge of the velocity structure. Introduction of fracture heterogeneities resulted in anomalous mislocated AE events. Decomposition of AE source mechanisms shows dominantly end-member behaviour between tensile and compressive vector dipole events, with very few double couple-dominated events and no purely tensile or compressive events. Calculations show that the crystallographic anisotropy of quartz causes apparent deviation of the moment tensors away from double couple and pure tensile/compressive sources consistent with the observations. Preliminary modelling of calcite anisotropy shows a response distinct from quartz, indicating that the effects of anisotropy on interpreting AE are complex and require detailed further study.

The Virtual Seismic Atlas – utilising web-based material in Earth science research.

Torvela, T. & Butler, R. W. H.
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Seismic data are expensive to acquire and process, yet give key insights into geological structure and processes, and have revolutionized understanding and modelling of Earth surface processes, structural geology, submarine hazards, properties of the lithosphere, etc. There is a substantial volume of seismic reflection data acquired by academic research programmes, national institutions, and companies. Although these data are mainly confidential, there are significant volumes of data that are within the public domain. However, the geosciences community is generally poorly connected to these data as they often are difficult to locate when looking for analogues for comparative study. The Virtual Seismic Atlas (VSA; www.seismicatlas.org) aims at correcting this problem by serving both as a resource for analogues and as a medium for distributing and promoting existing datasets and publications.

The VSA is an independent, free-to-use, community-based internet resource that captures and shares the geological interpretation of seismic data globally. The site can be browsed anonymously to find images and interpretations: the available images portray a variety of geological settings, in many cases accompanied by geological interpretations, links to related publications, etc., all searchable and downloadable. As such, the site also serves as a portal to other, more specialised seismic libraries, resources and publications. In short, the VSA provides a platform for the community to upload and promote their own work, while at the same time allowing an easy way of locating seismic examples and analogues, and to comparing interpretation strategies and experience. This can then drive new creative opportunities for research and teaching

This presentation provides an example of the possibilities the VSA offers for research geoscientists. Selected images of the seismic, all downloadable from the web site, are presented and interpretations of these are invited directly on the poster and/or on the hand-outs made available at the meeting.

Submission of content (including interpretations of existing images) can be achieved through the VSA management team (including the authors of this abstract) - contact us and we will set up a log-in. The VSA is a partnership between academia and industry and it is funded by the UK’s Natural Environment Research Council, the Petroleum Exploration Society of Great Britain, together with a consortium of companies (BG, BHPBilliton, Hess, Shell and StatoilHydro).

Visualising and understanding structural geology from the field to the lab: using Move as an aid in teaching and research.

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The future of structural geology relies on the current generation of students being adequately trained but there is a growing concern in both academia and industry that basic geological skills are fading. Classic field mapping skills, as well as the ability to visualise structures in three dimensions, are important skills developed during an undergraduate geology student's course of study. Successful development of spatial awareness is crucial for visualisation of geological structures, such as faults or folds, intersected by topography. A further higher order skill is to 'see' how these structures develop through time. To assist undergraduate students in learning key visualisation skills and structural geology concepts, and to aid lecturers in their teaching and research, Midland Valley have allowed free access to their structural modelling software, Move, for all academic institutions. The Move software can be used for data collection and applied to a variety of geological problems, from using it to digitally map structures in the field, to restore and balance 2D cross sections, to assisting students to visualise geological structures in three dimensions.

Move can be used on a toughbook PC in the field and has the functionality to provide a full digital workflow, incorporating use of Windows Journal as a digital notebook. Students have responded well to using digital technology in the field to collect and analyse data. The benefits of a digital workflow over a more traditional paper-based method include the opportunity to link field and lab work, quickly create cross sections, forward model possible scenarios, and see the data in three dimensions, including stereographically, whilst still in the field. Move gives the user the ability to test and validate the developing model through structural restoration, allowing an understanding of how the mapped structures may have developed through time.

Field and lab work can be linked with the use of Move in practicals, or as student led digital learning exercises. To support such use, Midland Valley has produced a set of interactive three-dimensional structural models designed specifically as a teaching aid using Move. The models have been created based on the deformation of a layer-cake stratigraphy. A set of 14 different geological structures have been created to help students visualise their three dimensional morphology, illustrate how the structures interact with topography and the resultant map patterns created. The models are designed to be interactive and a booklet, outlining workflows for the restoration and/or forward modelling of the structures, compliments the models. This allows the user (student or teacher) to forward model or restore a layer-cake stratigraphy e.g., restoring offsets along faults or forward modelling a thrust sequence. The ability to manipulate the models in this way helps students to visualise the formation and evolution of geological structures in three dimensions and to relate this back to outcrop patterns observed on a geological map.

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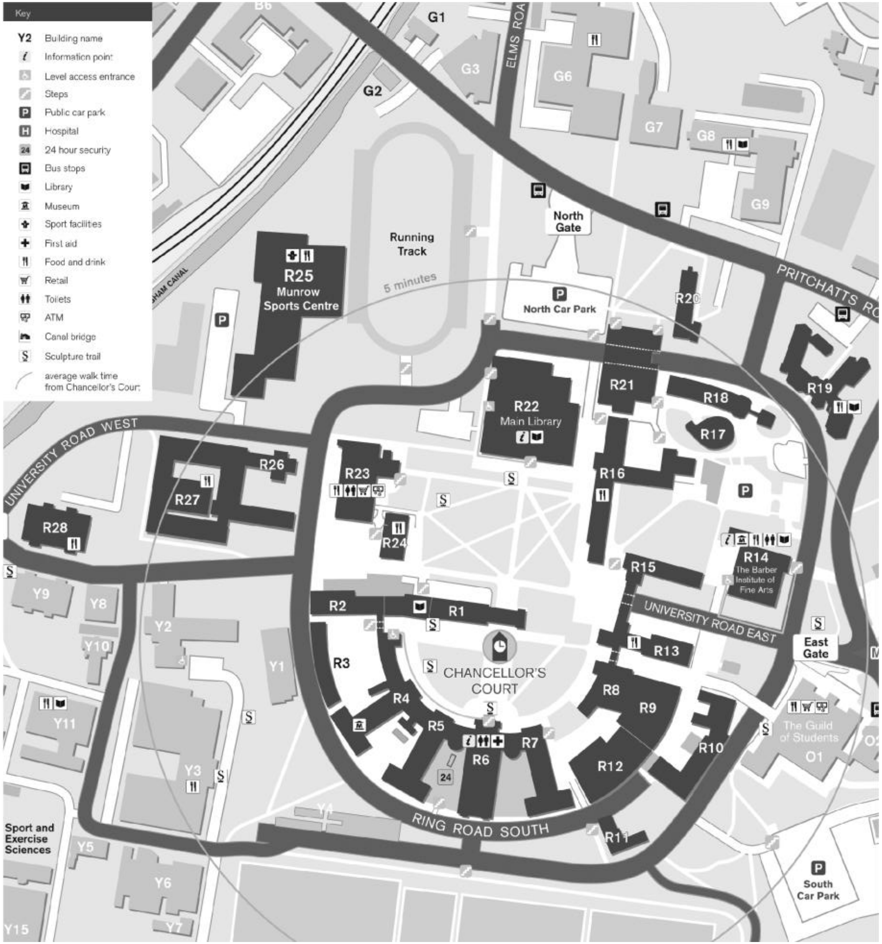
Edgbaston Campus Map

Index to buildings by zone

Red Zone

R1 Law
R2 Frankland Building
R3 Hills Building
R4 Aston Webb – Earth Sciences
R5 Aston Webb – B Block
R6 Aston Webb – Great Hall
R7 Aston Webb – C Block
R8 Physics West
R9 Nuffield
R10 Physics East
R11 Medical Physics
R12 Aitchison Building
R13 Poynting Building
R14 Barber Institute of Fine Arts
R15 Watson Building
R16 Arts Building
R17 Ashley Building
R18 Strathcona Building
R19 Education Building
R20 J G Smith Building
R21 Muirhead Tower
R22 Main Library
R23 University Centre
R24 Staff House
R25 Munrow Sports Centre
R26 Geography
R27 Biosciences
R28 Learning Centre



TSG 2010 post meeting workshop

Saturday 9th January 2010
Move2010 for teaching and research
Earth Imaging laboratory, Earth Sciences, University of Birmingham

Midland Valley Exploration's Academic Initiative's began three years ago and now, between the Field Mapping Initiative and the Academic Software Initiative, nearly 200 academic geoscience departments worldwide are using Move.

This workshop aims to introduce Move2010 to academic users and to highlight a few potential uses in teaching and research. We will go through some hands-on exercises from the Move2010 tutorials and discuss some current uses in academic teaching and research including field mapping.

Contact Carl Stevenson: c.t.stevenson@bham.ac.uk
Midland Valley will be represented by Dr Ruth Wightman.

Workshop Itinerary: cost: £7.50 *(on arrival)*

Time	Item
09.00 - 09.20	Introduction to Move and the rationale behind the ASI
09.20 - 11.00	Move2010 hands-on exercise - 2DMove
11.00 - 11.30	Refreshment break
11.30 - 12.30	Move2010 hands-on exercise - 3DMove
12.30 - 13.30	Lunch (Lapworth Museum)
13.30 - 14.00	Introduction to structural analysis - 4DMove
14.00 - 15.00	Examples of using Move in teaching and research
15.00 - 16.00	Examples of using Move in field mapping
16.00 - 16.30	Refreshment break
16.30 - 17.30	Participant Examples / Q&A

For further information visit the TSG website:
http://www.gees.bham.ac.uk/tsg2010.shtml.

The Earth Imaging lab is in Earth Sciences, building R4 on the map in this link: http://www.about.bham.ac.uk/maps/pdfs/edgbaston-map-red-09.pdf