Industrial Structural Geology
Principles, Techniques and Integration
28-30 November 2012

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# PROGRAMME

**Wednesday 28 November**

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| 9:05  | **Session 1: Regional & Basin Scale 1**  
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Opening Address: Joe Cartwright (Oxford University)  
What has Structural Geology Research Ever Done for You?  
Keynote Presentation: Nicky White (Cambridge University)  
Epeirogenic Elephants in the Orogenic Room |
| 9:45  | Alex Bump (BP)  
Subsidence History of the Arabian Plate: Setting the Stage for the World's Largest Hydrocarbon System |
| 10:25 | Coffee and Poster Session |
| 10:45 | **Session 2: Regional & Basin Scale 2**  
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Extension on Rifted Continental Margins: 2D Seismic Meets 3D Industry Realities |
| 11:00 | Alan Roberts (Badley Geoscience)  
Integrated Geodynamic Modelling as an Aid to Understanding Deepwater Rifted Continental Margin Structure and Location |
| 11:30 | Nick Kusznir (University of Liverpool)  
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| 11:50 | Sheona Masterton (Getech)  
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| 14:10 | Tiago Alves (Cardiff University)  
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| 16:20 | Sukonmeth Jitmahantakul (Royal Holloway University of London)  
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| 9:00  | **Frede Georgsen (Norwegian Computing Centre)**               |
|       | Fault Uncertainty Modelling                                   |
| 9:30  | **Lydia Jagger (Royal Holloway University of London)**        |
|       | Analogue Modelling of Inverted Domino-Style Fault Systems    |
| 9:50  | **Atle Rotevatn (Uni-CIPR)**                                  |
|       | How Long is a Fault? The Implications of (not) Understanding Fault Dimensions from Seismic Data in Exploration and Production |
| 10:30 | **Coffee and Poster Session**                                |

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|       | Structural controls on the preservation of pre-rift stratigraphy in the North Red Sea, Egypt |
| 13:20 | **Christopher Wild (Cardiff University)**                    |
|       | Kinematic Indicators of Strike-Slip Faults in 3D Seismic Data: Implications for Fault Propagation, Levant Basin |
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| 14:20 | **Bob Holdsworth (Durham University)**                       |
|       | Absolute age dating of faulting using rhenium-osmium (Re-Os) geochronology in ore deposits and hydrocarbon basins |
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## Friday 30 November

### Session 9: Development, Fractures and Geomechanics 1
**Chairs: Richard Fox and Paul MacKay**

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<td><strong>Michael Welch (RDR)</strong></td>
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**Chairs: Caroline Gill and Woody Wilson**

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<td>A Geomechanical Study of the Gorm Field, Danish Central Graben: Predicting Fracture Density, Orientation and Hydraulic Behaviour in a Chalk Reservoir</td>
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<td>Testing restoration-based fractures prediction within a fault damage-zone in carbonate rocks: the Filettino fault, Central Apennines, Italy</td>
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<td>Petrophysical Anisotropy in Faulted Porous Sandstones</td>
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Oral Presentations

Abstracts

(Presentation order)
Wednesday 28 November

Session One: Regional and Basin Scale

Chairs: Frank Richards & Nick Richardson
Opening Address: What Has Structural Geology Research Ever Done For You?

Joe Cartwright, Department of Earth Sciences, Oxford University, South Parks Road, Oxford OX1 3AN

The petroleum industry has been a great supporter of academic structural geology research over the past few decades. This presentation reviews some of the advances that have come from structural research in an effort to see whether the funding effort has been worthwhile. More specifically, we can legitimately ask the questions ‘should the petroleum industry continue to support academic structural geology and how best can it do this?

Starting with improved understanding of basin evolution in the 1970s, major advances followed in the interpretation of structural styles on seismic data in the 1980s. In particular, the largely government-funded deep seismic reflection programmes of the 1980s (e.g. BIRPS) had a significant impact on our understanding of rift basin architecture, and forced us to think of the link between rift bounding extensional faults and their often orogenic precursors. Field and analogue modelling studies started to play a significant role in subsurface structural interpretation at this time, exploiting ideas and approaches that were shaped much earlier by entirely curiosity-driven research (1920s-30s).

Perhaps one of the most influential developments of the modern era was in the late 1980s and early 90s with the advent of a new methodology for analysing faults. This stemmed from an initial curiosity of Juan Watterson, but with the partnership with John Walsh blossomed into a full-blown assault on the way we handle fault interpretation. For impact on the business, this is probably only matched by the massive advances in salt tectonics inspired largely by Martin Jackson and colleagues in the BEG. To see how far this work has taken us, just think how hard it is to look back to what we understood of salt behaviour in say 1980, and imagine how we ever dared interpret salt structures on seismic data at all!

There are many other examples of themes that have had massive impact, that stem largely from university-based research, and not all of it has been industry funded. Indeed, it could be argued that most major advances have come out of native curiosity. Given that nearly all current industry funding for structural research is short-termist in ambition and scope, is there a danger that we will cut off the goose that lays the imaginative and impact-laden egg? Yes!
NOTES
Keynote Presentation: Epeirogenic Elephants in the Orogenic Room

Nicky White, Bullard Laboratories, Department of Earth Sciences, University of Cambridge, CB3 0EZ

Since the 1960s, the enormous success of plate tectonics has conditioned the way in which we think about large-scale structure and deformation. For example, the generation of elevated topography is often linked isostatically to episodes of crustal and lithospheric shortening, which are ultimately controlled by horizontal plate motions. Despite this success, there is good evidence that the 'tyranny of isostasy' does not always prevail and that some fraction of topography is supported by subplate processes. For example, the crustal thickness beneath Northwest Scotland (~25 km) is smaller than that beneath London (~32 km) but the elevation difference suggests the opposite. On a larger scale, the crustal thickness beneath Colorado and Michigan is the same (~40 km) but the elevation difference is ~2 km. In both cases, measurable horizontal shortening is several orders of magnitude smaller than that required to support elevation by crustal or lithospheric isostasy. Something else must be going on but what is it? A number of lines of evidence suggest that convective circulation of the Earth's mantle maintains plate motion. However, we know little about the spatial and temporal details of this circulation. It is reasonable to expect that this circulation pattern generates dynamic topography at the Earth's surface. On the continents, small dynamic topographic signals have historically been difficult to measure because the density structure of the crust and lithosphere usually controls surface elevation. Useful progress can be made by exploiting our quantitative understanding of the thermal evolution of oceanic lithosphere. We have analyzed seismic reflection and wide-angle profiles from the oldest oceanic lithosphere which abuts continental margins worldwide. First, we calculated the water-loaded depth of old oceanic lithosphere adjacent to various margins. Secondly, we estimated residual depth anomalies by comparing our water-loaded depths to the global age-depth curve. These residual depth anomalies can then be compared with dynamic topographic predictions made from long-wavelength gravity and seismic tomographic anomalies. Positive and negative deviations from the global age-depth curve are common and have amplitudes of ~1 km and wavelengths of 10^2-10^4 km. They mostly, but not always, correlate with long-wavelength gravity anomalies. The distribution of dynamic topography through-out the rest of the oceanic realm can be supplemented by using ship-track data in regions with sparse sedimentary cover, by exploiting the mid-oceanic ridge system, and by examining the age-depth relationship in marginal oceanic basins. Our surprising results have important implications for the origin of continental topography. Along the West African margin, a series of broad structural domes straddle the continental shelf. Sequence stratigraphic geometries and drainage networks demonstrate that these gigantic features mostly grew in Neogene times, triggering large-scale salt deformation along adjacent deep-water margins. Along the Northwest Shelf of Australia, a broad depression intersects the coastline. Post-Miocene growth of this depression is recorded in a dramatic switch from aggradation to progradation within a carbonate reef deposit. This switch caused source rocks at depth to enter the hydrocarbon window and charge overlying traps. Our results have broad implications for the development of structure, stratigraphy and drainage along continental margins and within the adjacent interiors. Accurate maps of the spatial and temporal patterns of dynamic topography will illuminate our understanding of the relationship between surface-structural geology and deep Earth processes.
Subsidence History of the Arabian Plate

Alex Bump, Alistair Crosby, BP

The Arabian plate is dominated by three main basins, the Zagros foredeep, the Rub Al Khali and the Widyan-Mesopotamian. The first of these, the Zagros foredeep, runs the length of the Zagros thrust belt, parallel to the mountain front. It contains as much as 8-10 km of Mesozoic and Cenozoic sediments over a largely unknown but probably attenuated Paleozoic section. The second, the Rub Al Khali, is a roughly circular intracratonic basin, centered in southern Saudi Arabia. It holds a remarkably complete section of latest Precambrian through Cenozoic sediments that reaches as much as 8-10 km in thickness. Indeed, in the basin center, the only major gap in the sedimentary record is the Hercynian unconformity of Carboniferous age which truncates the Carboniferous and Devonian sections. The third basin, the Widyan-Mesopotamian is also a roughly circular, intracratonic basin centered roughly on the border between western Iraq and northeastern Saudi Arabia. Like the Rub Al Khali, it is a deep basin, reaching 10-12 km in its center. Unlike the Rub Al Khali, however, the fill is dominated by latest Precambrian and Palaeozoic sediments overlain by only a thin veneer of 1-2 km of Mesozoic and Cenozoic sediments. Notable local exceptions to this description are younger structural features such as the Palmyride and Sinjar troughs and the Euphrates graben. Despite the large accumulations of sediment, the Palaeozoic subsidence mechanisms behind these basins are not immediately obvious.

To address this question, we compiled a series of 34 stratigraphic columns, based on well logs, measured sections, seismic data, and depth-to-basement maps. Using software developed by Cambridge University, we back-striped each of these columns and created water-loaded subsidence curves. All of these show rapid subsidence in the latest Precambrian and early Cambrian, followed by steadily declining subsidence rates thereafter. In the Rub Al Khali, the subsidence rate tapers off very slowly, interrupted only by brief episodes of more rapid subsidence in the Permo-Triassic and locally in the Late Jurassic. Subsidence continues to the present day. In the Widyan-Mesopotamian Basin the subsidence rates taper off much more rapidly, going to almost zero by the Mesozoic. Some younger graben (such as the Palmyride and Sinjar troughs) superimposed on the Widyan Mesopotamia basin show the same, brief Permo-Triassic and Late Jurassic episodes of rapid subsidence seen in the Rub Al Khali. Likewise, models in the Zagros foredeep also show brief episodes of rapid Permo-Triassic and Late Jurassic subsidence with intervening periods of slower and declining subsidence rates.

These model results suggest that the three main Arabian basins originated as extensional basins with brief periods of rapid, tectonically-driven subsidence, followed by longer periods of slow, thermally-driven subsidence. Regional geological maps do show Pre-Cambrian calcalkaline and tholeitic volcanics, the transtensional Najd fault system and extensional grabens filled with coarse clastics and evaporites. Extension was clearly taking place. However, the observable faults do not account for the 30% extension suggested by the subsidence models. Moreover, maps of present-day lithospheric thickness do not show the large differences between the Rub Al Khali and the Widyan-Mesopotamian basins required by the models to explain the differing rates of thermal subsidence. An extensional origin for these basins thus remains a preferred but unproven interpretation.
Session Two: Regional and Basin Scale

Chairs: Nick Richardson & Frank Richards
Invited Speaker: Extension on Rifted Continental Margins: 2D Seismic Meets 3D Industry Realities

Jakob Skogseid, Ole Jacob Martinsen, Scott Young, Statoil ASA

Mapping the signature of extensional deformation on rifted margins is often hampered due to coverage by thick sedimentary or volcanic successions, or because salt tectonics makes sub-salt seismic imaging a real challenge. Over the past 20 years the literature is witnessing that lack of mapped faults have resulted in a variety of both analogue and numerical models based on the assumption that the upper crust takes only little extensional thinning, while the reduction of crustal thickness is taking place in the middle and lower crust, as well as in the mantle.

In this presentation two case studies, in combination with plate kinematic models, are used to highlight the difference that 3D seismic data may have on our understanding, and to argue for how the small patches of 3D resolution, from a plate kinematics point of view, may allow us to extrapolate from one margin segment to the next.

In the South Atlantic salt tectonics represents a major problem for sub-salt imaging. The conjugate margins of Brazil and Angola are, however, characterized by pronounced crustal thinning as documented by crustal scale 2D reflection and refraction data. Off Angola the 3D ‘reality’ demonstrates that upper crustal extension by faulting is comparable to the full crustal, as well as lithospheric thinning as derived from refraction and basin subsidence analysis. The mapped faults are listric low angle faults that seem to detach at mid crustal levels. 2D seismic has in the past been interpreted to indicate that almost no extensional faulting can be mapped towards the base of the so-called ‘sag’ basin. The whole concept of the ‘sag’ basin, often ascribed to as crustal thinning without upper crustal deformation, is in fact related to this ‘lack of observation’, and furthermore, have caused the making of different types of dynamic models attempting to account for this.

In the NE Atlantic significant Paleocene extensional faulting is locally seen adjacent to the 50 to more than 200 km wide volcanic cover on each side of the breakup axis. The associated amount of lateral motion on these, mainly listric, normal faults represents several tens of km. These observations contrast with the general lack of observed faults along volcanic margins due to the overall problem with sub-basalt imaging. A variety of models with respect to mode and duration of extension, including narrow and fast breakup, melt generation by small scale convection, and different modes of mantle flow have been suggested. The interesting aspect is that it is all based on features we can’t see.

Both study areas clearly points towards the importance of improved seismic imaging, a need for revised understanding of strain rates and strain partitioning during rift development, and the necessity of moving from 2D cross section modeling to more realistic 3D spatial distribution of rift elements and subsequent break-up processes. The importance in a petroleum exploration perspective is that both volcanic and non-volcanic margins are rifted margins formed by a protracted rift development. The ‘new reality’ scenario has significant influence on heatflow modeling and the separation of syn- vs post-rift subsidence and associated sedimentation. In fact the ‘sag basins’ may simply be viewed as post-rift but pre-breakup basins elements.
Integrated Geodynamic Modelling as an Aid to Understanding Deepwater Rifted Continental Margin Structure and Location

Alan Roberts

Nick Kusznir, Richard Corfield, Mark Thompson, Richard Woodfine

1 Badley Geoscience
2 Liverpool University
3 BP Exploration

An integrated workflow has been devised for the investigation of deepwater rifted continental margins. This allows us to predict the crustal structure, the distribution of continental-lithosphere thinning and the location of the ocean-continent-transition with a new degree of confidence. The workflow combines the analytical techniques of 2D or 3D gravity inversion, flexural backstripping, fault-extension analysis and forward modelling, augmented by prediction of top-basement heat-flow history. No one technique on its own can provide all of the required answers, nor can it provide answers without some degree of uncertainty. The use of a combination of techniques, however, provides answers to several different problems and crucially more confidence in these answers.

2D/3D gravity inversion Key to the gravity inversion is the incorporation of both a lithosphere thermal gravity-anomaly correction addressing the elevated post-breakup lithosphere geotherm and a prediction of new volcanic crustal addition at high stretching factors. This allows us to predict (i) depth to Moho, (ii) thickness of residual continental crustal-basement, (iii) location of the OCT, (iv) heat-flow history, incorporating the lithosphere’s first-order responses to extreme thinning.

2D/3D post-breakup flexural backstripping “Traditional” backstripping and knowledge of the margin stratigraphy is used to quantify the long-term post-breakup subsidence history of continental margin lithosphere. This allows us to predict the spatially-varying magnitude of the whole-lithosphere thermal anomaly and stretching factor resulting from the breakup process. It is a simple but powerful technique to employ as the fundamental requirement is simply a 2D or 3D model (cross-section or maps) of the post-breakup stratigraphy.

2D/3D syn-kinematic flexural backstripping At many margins the location of the base post-breakup sequence is uncertain or unknown, particularly at margins where mobile salt is involved. The base of the syn-rift/breakup sequence may, however, be more easily identified. Backstripping to reveal the total syn-plus-post-breakup water-loaded subsidence allows us to convert subsidence to estimates of lithosphere thinning-factor allowing for the isostatic consequences of syn-breakup volcanic addition (underplating), a process which in turn leads to the formation of new ocean crust. From this we can map crustal basement thicknesses, the OCT and heat-flow history in a comparable way to the results of the gravity inversion.

Quantifying upper-crustal fault extension Gravity and subsidence modelling aim to quantify extension of the whole crust and/or lithosphere. We believe that the process of depth-dependent lithosphere-thinning during breakup means that upper-crustal extension need not necessarily balance these estimates of deeper stretching and thinning. It is therefore important to quantify fault-controlled upper-crustal extension either by forward modelling or section restoration. This provides information about the partitioning of extension through the crust, which ultimately impacts upon the detail of the top-basement heat-flow model.

Forward modelling the kinematics of breakup Finally we aim to bring together the complete rifting/breakup process within a single forward model, incorporating observations from the previous analyses in its construction. The forward model of full (conjugate) margin lithosphere structure is calibrated against backstripped-subsidence predictions and also bathymetry and gravity measurements. It is used not just to predict the crustal structure and evolution of the margin, but also to predict heat-flow history, as controlled by the kinematics of the breakup process.
Examples of each of the above are illustrated with reference to the Brazilian, NW Australian, Indian, North Atlantic and Norwegian continental margins.
Mapping Continental Margin Crustal Thickness and Ocean-Continent Transition Using Satellite Gravity Inversion: A New Frontier Exploration Technology

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The investigation and mapping of rifted continental margins and ocean basin development is the focus of much current attention motivated by hydrocarbon exploration, territorial claims and geo-dynamic research. Satellite gravity anomaly inversion incorporating a lithosphere thermal gravity anomaly correction has been used to determine Moho depth, crustal thickness and continental lithosphere thinning for oceans and continental margins worldwide. These parameters are used to locate the ocean-continent transition and the distribution of microcontinent along rifted continental margins and adjacent ocean basins.

Using a new gravity anomaly inversion method, which incorporates a lithosphere thermal gravity anomaly correction, we have produced a global suite of maps showing crustal thickness and oceanic lithosphere distribution for all of the world's oceans and adjacent margins. Here we focus on results from two geographic regions: Asia-Pacific and the Indian Ocean.

Maps of continental lithosphere thinning factor and crustal thickness from gravity inversion provide predictions of ocean-continent transition location independent of magnetic isochrons (that are often difficult to interpret). Superposition of shaded-relief free-air gravity onto crustal thickness maps from gravity inversion provides improved determination of pre-breakup rifted margin conjugacy and sea-floor spreading trajectory. Crustal thickness & continental lithosphere thinning maps from gravity inversion restored to early post-breakup times show the geometry and segmentation of the margin at the time of breakup together with the location of failed breakup basin and micro-continents. The abundance of anomalously thick crust within oceanic regions, interpreted as possible micro-continents and often associated with multi-phase volcanism, suggests that the development of the world's oceans has a more complex history than is shown by most large-scale plate reconstructions.
Atlantic Fracture Zones as Indicators of Changing Plate Tectonic Stress and Their Link to the Evolution of Intra-Continental Rift Basins

Masterton, S. M., Fairhead, J. D., Green, C. M., Getech, Leeds, UK.

It has been a long held view that oceanic fracture zones (fzs) play an important role in the segmentation of continental margins and therefore provide a major structural control on their evolution and the development of associated petroleum systems. The geometry of fzs reflects the spreading history of the seafloor: subtle changes in plate motion cause stress-field reorientation, which in turn results in changes in the orientation of the fracture zones. These changes can introduce strike-perpendicular compression or extension across transform faults; the latter may lead to increased ridge segmentation and the initiation of new spreading centres.

We present two examples of secondary fz initiation and disappearance within the Atlantic Ocean between 1) the Atlantis and Kane major fzs in the Central Atlantic and 2) the Ascension and Rio de Janeiro fzs in the South Atlantic. We investigate the discontinuous nature of these fzs by exploring their relationship with major plate re-organisation events and seafloor spreading geometry. Using a series of stage reconstruction poles that represent the motion of both North and South America relative to Africa since the initiation of Atlantic seafloor spreading, we have performed a quantitative analysis of spreading directions along major Atlantic fzs.

The Atlantis and Kane major fzs extend across most of the width of the Central Atlantic (Figure 1a) and record the relative motion between North America and Northwest Africa. At ~80 Ma, North America began to rotate anti-clockwise relative to Northwest Africa; this change in plate motion is likely to have been a direct response to major plate re-organisation associated with the Santonian compressional event (e.g. Guiraud and Bosworth, 1997). It is recorded as a change in the orientation of both these major fzs (Figure 1a, b). The rate of anti-clockwise rotation significantly increased shortly after this.

![Figure 1](image)

Figure 1 a) The Atlantis and Kane fzs in the Central Atlantic with labelled crustal ages (at black ticks) in Ma. Selected isochrons (Cande et al., 1989) are overlain onto free air gravity based on the Trident satellite solution (Fairhead et al., 2009). A series of short parallel fzs (highlighted black lines and inset) appear in the gravity signature at ~65 Ma; b) Fracture zone azimuth against seafloor age.

Whilst many major fzs in the Atlantic are observed to extend to the continental margins, a distinct region exists between the Ascension and Rio de Janeiro fzs in the offshore Angolan region and the conjugate offshore Brazilian margin, where no fzs are observed (Figure 2a). Sedimentation, unless very thick and regional in extent, is unlikely to totally explain the apparent absence of fzs, although sedimentary fill will dampen/reduce their gravitational response. Furthermore, the regions are distinctly symmetrical, suggesting that their presence is associated with ridge processes rather than post-emplacement sedimentation.
Figure 2  a) The Ascension and Rio de Janeiro fzs in the South Atlantic with labelled crustal ages (at black ticks) in Ma. Selected isochrons (Cande et al., 1989) are overlain onto free air gravity based on the Trident satellite solution (Fairhead et al., 2009). No fzs are observed in the conjugate offshore Angolan and Brazilian regions; b) Fracture zone azimuth against seafloor age.

Comparison of fz geometry with isochron locations suggests that the initiation of fzs a) occurred at or shortly after ~84 Ma, and b) coincides with a subtle change in fracture zone orientation. We suggest that these observations are the result of major plate re-organisation associated with the Santonian compressional event that disrupted the previously stable spreading centre geometry and led to a period of ridge reorientation in order to re-establish stability within the system. This interpretation is consistent with both the subtle, but observable bend in the Ascension Fracture Zone (Figure 2a) and our fz azimuth-age plot (Figure 3b) that shows an increase in the rate of clockwise motion of South America relative to Africa at 84 Ma. Furthermore, the geometry and sense of changes in relative plate motion at this time would have generated a trans-tensional stress field that resulted in increased ridge segmentation.

On a regional scale, the evolution of the Africa-wide Mesozoic rift system is intimately linked to global plate tectonics and to changes in plate interactions. On a basinal scale, changes in the orientation of the dominant stress field resulting from plate reorganisation have had a clear impact on the deformation history and fault geometries of rift basins. We observe this relationship based on the temporal correlation of changes in South Atlantic fz geometries and African margin unconformities with major unconformities that are observed in a unified stratigraphy chart for the West and Central African Rift System.
Session Three: Regional and Basin Scale

Chairs: Simon Stewart and Steve Rippington
Keynote Speaker: Coeval Extension and Shortening Above and Below Salt Canopies on an Uplifted, Continental Margin: Application to the Northern Gulf of Mexico

Martin P.A. Jackson, Tim P. Dooley, Michael R. Hudec, Applied Geodynamics Laboratory

Recent ultradeep exploration in the northern Gulf of Mexico has revealed a broad, diffuse zone of salt-cored folding beneath the present continental shelf. This zone is a pillow fold belt, where salt pillows grew by halokinesis and were then mildly shortened. Below the Louisiana shelf a contractional early-to-late-Miocene pillow fold belt is separated from an overlying early-Miocene-to-Pliocene extensional system by a partly welded canopy. This anomalous juxtaposition raises two paradoxes. (1) Why was middle Mid-Miocene shortening close to the Miocene shelf break where extension is expected? (2) Why did shortening below the canopy overlap in time with extension above the canopy?

Coastal uplift can explain both paradoxes. Cenozoic uplift and exhumation of the northern rim of the Gulf of Mexico created coastal offlap and truncation around the rim. Uplift tilted the continental margin and overpowered the influence of the paleoshelf break. As a result uplift caused shortening to spread much farther updip. Physical models confirm that this hypothesis is mechanically sound. Coeval subcanopy shortening and supracanopy extension result from two stacked detachments, each kinematically pinned in different places. The deep autochthonous detachment was pinned far inland, equivalent to the uplifted continental interior. Extension above this deep detachment was balanced by shortening far downdip to form a pillow fold belt, where a network of thrusts links squeezed pillows. In contrast the shallow allochthonous detachment was pinned farther seaward, equivalent to the upper continental slope. Extension occurred above this canopy, overlying the shortening below.
Diachronous Gravitational Gliding of Albian Rafts Offshore Brazil

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Gravitational collapse of carbonate rafts is a ubiquitous phenomenon on many South Atlantic continental margins. As rafts can be welded onto pre-salt units, at the same time being sealed by fine-grained units, they have the potential to accumulate large quantities of hydrocarbons in regions such as SE Brazil and West Africa.

A three-dimensional (3D) seismic-reflection volume from the Espírito Santo Basin was used to quantify the geometry and significance of normal faults reactivated during the gravitational gliding of Albian rafts. In the study area, a series of well-dated unconformities intersect reactivated strata showing distinct fault families. In such a setting, Late Cretaceous gravitational instability led to the fragmentation of Albian strata in individual rafts separated by listric (roller) faults and associated sub-basins (Stage 1). Renewed gravitational gliding caused Albian rafts to be translated downslope until salt welds were formed and Albian strata became grounded over pre-salt sequences (Stage 2). Diachronous grounding promoted the reactivation of faults and folds, which at places developed into pop-up structures and broad anticlines sub-parallel to the strike of individual rafts (Stage 3).

This work presents a new method to identify and date reactivated fault families and shortened anticlinal structures adjacent to Albian rafts. Statistical analyses of six main fault families confirm that fault reactivation depended on: i) the complete grounding of Albian rafts or, ii) gravitational stabilization of the rafts imposed by sediment loading and cessation of tectonic tilting of the slope.

In this work is shown that relationships between deep rafts and overburden faults include: a) roller faults developed over the oceanward flank of deep rafts, often in association with preserved triangular salt rollers; b) triangular structures formed above rafted blocks of Albian strata, and bounded oceanwards by roller faults, and landward by faults antithetic to the master roller faults; c) pop-up structures with reactivated crestal/keystone and rollover faults usually located on the landward flank of rafts, where lateral shortening is recorded; d) concentric faults only present at the north and south tips of Cretaceous sub-basins; e) pop-up structures located on the flanks of rollover anticlines, with central parts of these anticlines recording very moderate (if any) reactivation (Figure 1).

Main conclusions are that shortened structures in the study area are markedly diachronous and accommodated up to 10% of post-salt overburden shortening. Such a magnitude of shortening was mainly achieved in regions where buttressing of gliding post-salt strata occurred onto triangular structures formed above welded Albian rafts, or where a balance was established between overburden loading and slope gradient imposed by tectonic uplift.

The results of this study show that other mechanisms than tectonically-related horizontal shortening can deform post-salt overburden units in proximal extensional-dominated regions of southeast Brazil. This is a key piece of data for geodynamic reconstructions, as it proves that a continuum of overburden deformation, rather than discrete episodes of inversion, may occur on continental margins dominated by raft tectonics.
Figure 1 – Selected seismic sections showing evidence for local reactivation of normal faults and rollover anticlines. Figure a) shows reactivated roller faults with prominent on hanging-wall and footwall blocks. Buttressing occurs onto a grounded raft observed at depth. Panel b) shows a pop-up structure truncated by Horizon 5. Modified from Alves (2012).
The Origin of Separate Oil and Gas Accumulations in Adjacent Anticlines in Central Iran


In Central Iran two adjacent anticlines contain hydrocarbons within the Late Oligocene-Early Miocene Qom Formation. The anticlines formed at approximately similar times (Late Miocene-Pliocene), have similar overall geometries, but the Alborz Anticline is an oil field, while the Sarajeh Anticline is a gas field, and both are underfilled structures. Basin modeling and structural restorations identified why the two different accumulations developed. The Sarajeh and Alborz anticlines are modified detachment anticlines. Asymmetric development of growth strata on the SW margin of the folds was caused by salt withdrawal and normal fault activity on the basin margin, which modified the detachment fold style and tilted the basal detachment to the SW. The detachment dies out to the NE as the basal (Lower Red Formation) evaporites pinch out in the same direction, yet the Alborz Anticline is north vergent, while the Sarajeh Anticline is south vergent. The mini salt-withdrawal basin is best developed on the southern limb of the Sarajeh Anticline and is responsible for the SW vergence. This difference in vergence permitted the Alborz Anticline to attain 4-way dip closure earlier in its structural history than the Sarajeh Anticline, and consequently the trap was at least partially developed as a four-way closure during oil generation and expulsion. For the Sarajeh Anticline oil migrated across the fold when it was still unclosed, subsequent subsidence of the SW fold limb resulted in gas generation and expulsion during the time when the fold attained closure.
Session Four: Regional and Basin Scale

*Chairs: Simon Stewart and Steve Rippington*
Keynote Presentation: The Association of Folding and Fracturing and the Bulk Properties of Fracture Networks

John Cosgrove, Imperial College London

No Abstract
The 4D Evolution of Segmented Rift Systems: Insights from Scaled Physical Models

Sukonmeth Jitmahantakul, Ken McClay, Fault Dynamics Research Group, Department of Earth Sciences, Royal Holloway University of London

The four dimensional evolution of extensional faults in segmented rift systems has been simulated by scaled analogue models using wet clay packs. Models were recorded by high-resolution digital photography and the results analyzed using digital image correlation in order to monitor strains and displacements in the models as they evolved. Extensional deformation of 90° (orthogonal), 75° & 60° obliquely segmented rift models produced similar overall rift structures. Distinct offset graben systems were formed in all of the clay models. Offset depocentres were separated by extension-parallel accommodation zones of interlinked faults above the steps in the basal zone of stretching.

Analogue models of segmented rifts characteristically produced segmented rift-border fault systems controlled by the zone of stretching at the base of the model. With increased extension the border fault systems became linked by synthetic relay ramps. These faults were oriented sub-parallel to the segmented edge of the underlying base-plate. In contrast, intra-rift faults were developed perpendicular or at high angles to the extension direction. Analyses of the initiation, growth and linkage of the extensional fault systems in segmented rift models indicate that the accommodation zones and linked intra-rift faults remained active throughout the experiments and controlled rift basin development along the length of the segmented rift. Linked intra-rift faults moved and rotated during extension. These major faults formed by propagation and linkage of smaller faults. The degree of fault rotation depended upon the obliquity of the rift system with respect to the regional extension direction.

The analogue models of segmented rift system provide powerful visual templates for the interpretation of rift fault systems in the subsurface particularly where geometries are controlled by pre-existing structures. The experimental results are compared to natural examples of segmented rift systems such as those in the East African rift system and those on the North West Shelf of Australia.
Fold and Thrust belts are contractional systems created by plate collisions. These collisions create stress conditions where the maximum and intermediate principal stresses are horizontal and the minimum principal stress is vertical. The stress orientation favours the development of low angle reverse faults consistent with Anderson’s rules. Though the stress orientation is important in the determination of the fault orientation, the shape of the thrust system is also dependent on a wide variety of semi-related rates. Rates of uplift, erosion, deposition all play a role in the shape of the thrust belt. Spatial variations in sedimentary thickness, rock properties, and the relief on crystalline basement also have a profound effect on the development of the thrust belt.

Another fundamental influence on thrust belts is the presence of fluids within the geologic section and the role these fluids play as a trigger mechanism for seismic failure of faults. Failure occurs in the crust when the differential stress conditions within the crust (the difference between the maximum and minimum principal stresses) exceeds the strength of the crustal material. The effect of increased fluid pressure is to reduce the effective stresses within the system but maintain a consistent differential stress. Thus increasing fluid pressure is an effective trigger mechanism to create failure conditions in the section and allow faults to slip. As faults slip the fluids have an escape route and leave the system thus reducing the fluid pressure and re-establishing stability conditions effectively arresting the slip on the fault. Motion on the fault ceases until the fluid pressure elevates and recreates the failure condition thus repeating the process.

Within the sedimentary section the principal fluids available are water and hydrocarbons. Water is an effective mechanism to increase fluid pressure in relatively young unconsolidated sediments as those sediments compact; but in older more consolidated strata there is little water available to sustain prolonged deformation periods. The generation of hydrocarbons appears to be a more effective mechanism to create sustained elevated fluid pressure and to maintain that fluid pressure within a leaky system. Organic material goes through a volume increase when heated and converted to hydrocarbons. This volume increase creates substantial over-pressure fluid conditions within the rock as a greater volume must be confined within a restricted pore volume. The generation of hydrocarbons are a sustained source of fluids that may be used to create episodic elevated fluid pressures and failure within a thrust belt.

The flush of hydrocarbons during deformation results in abundant petroleum traps where the structural development and hydrocarbon charge are simultaneous. There are several nuances which add to the complexity of the system. Erosion has a greater effect where it both lightens the weight of the overburden on the active thrust belt but in some cases also compromises the top seal no longer allowing fluid pressures to build up and likely retarding the continuity of deformation. Another implication to this system is that the migration pathways become predominantly horizontal rather than vertical. The flush of hydrocarbons will migrate beyond the thrust belt into the adjoining foreland basin forming massive hydrocarbon resource deposits within the undeformed strata. In the case of the Canadian Rockies the lateral migration of hydrocarbons is hundreds of kilometres in distance to the point where the flush of hydrocarbons coming from the thrust belt has migrated to the other side of the foreland basin to form the massive oilsands bitumen deposits at the Alberta/ Saskatchewan border.
Thursday 29 November

Session Five: Prospect Scale

Chairs: Clare Bond & Douglas Paton
Keynote Speaker: Structural Trapping of Buoyant Fluids

Graham Yielding, Badley Geoscience Ltd

Structural traps comprise assemblages of surfaces that have high capillary threshold pressure for a fluid phase such as hydrocarbon or carbon dioxide. Individual traps may include top-seal, bottom-seal and side-seal surfaces, the latter commonly being formed by a fault.

Faults may form sealing surfaces in two quite separate ways:
(i) by juxtaposition, so that intervals of high capillary threshold pressure (such as shales) are juxtaposed against the reservoir unit within the trap; and
(ii) by fault-rock, in which new material (generated during fault slip) forms a barrier to lateral flow even when reservoir units are juxtaposed at the fault.

In order to risk prospect volumes in the exploration and appraisal process, the first step in fault characterisation is to map the distribution/juxtaposition of offset layers at the fault surface. This pattern (‘Allan diagram’) is captured by the set of separation polygons, i.e. the horizon/fault intersection lines in three dimensions. These same lines define the displacement distribution on the fault surface, and so can also be used as a quality-check on the interpretation, since it is well established that displacement patterns of faults and fault networks are controlled by a high degree of geometric and kinematic coherence. The separation polygons are also a fundamental part of horizon maps, since they are how the faults are represented on structure maps. Despite their central role in subsurface mapping, construction of fault polygons remains a weak step in the workflow in many E&P companies.

Fault rocks are generated from the wall-rock layers being slipped past each other at the fault and so their composition is determined by the wall-rock lithologies and the amount of displacement. The detailed internal structure of the fault rock is impossible to predict and hence it is usual to consider an upscaled proxy such as Shale Gouge Ratio, with the assumption that high SGR represents clay smears and low SGR represents clay-poor fault rock such as disaggregation zone or cataclasite. Suitable estimates of hydraulic properties can then be applied to different parts of the fault surface.

Even when the juxtaposition pattern and fault-rock distribution both indicate that a fault is likely to be sealing to cross-fault flow, there is a remaining risk that buoyant fluid may escape out of the trap up the fault plane. Such up-fault leakage can occur simultaneously with across-fault seal. It is dependent on the stress state of the fault, in particular how close the surface is to being critically stressed. The stress state is itself dependent on the reservoir pore-pressure, and so can be changed during trap filling or by reservoir management. In the latter case, pore-pressure changes during production/injection may be sufficient to induce slip on previously inactive faults. For major CO₂ storage projects, monitoring of subsurface pressure distribution is therefore required to avoid inducing seismicity and associated fluid leakage. In onshore areas, geomechanical modelling combined with high-resolution InSAR provides a particularly efficient monitoring workflow.
Fault Uncertainty Modelling

Frode Georgsen, Per Røe, Anne Randi Syversveen, Norwegian Computing Center

Introduction

The existence, position, shape, size and displacement of faults play an important role in several aspects of reservoir modelling including flow simulations, volume calculations and well planning. To model the faults, seismic inputs with both interpretation and migration uncertainty and well observations with uncertainty in log interpretations are applied. Uncertainty in the interpretation of the horizons causes uncertainty in the fault displacement. All these different sources of uncertainty should be included in the fault modelling.

The relationship between faults and their size and shape defines the compartments of the reservoir and influences the simulated flow paths. The modelling of the fault displacement can have great impact on whether the fluids flow through the fault or the fault acts as a barrier in the model. The joint uncertainty in the position and size of boundary faults plays a role in the volume estimation, and this uncertainty should be accounted for also in well planning to avoid drilling outside the desired area or directly through a fault.

We will present a fault modelling tool where different realizations of the structural model related to the above mentioned uncertainties can be generated. This is done by using a flexible representation of the faults which lets us update the fault geometry, fault displacement and fault size both in deterministic and stochastic ways.

Methodology

We will show how uncertainty envelopes around faults can be generated. These envelopes are based on seismic uncertainty and define the space for the fault to reside in. Both stochastic and deterministic change of position and shape of the fault can be performed within the envelope (See Figure 1). The envelope and fault position can be conditioned to well data.

![Figure 1: Seismic cross-section with interpreted fault surface in black and boundary surfaces of interpreted fault uncertainty envelope in blue (left). Two realizations of fault conditioned to one well observation (middle and right)](image)

The displacement and the length of the faults can be modified by deterministic or stochastic processes. The displacement is modelled by elliptic trends combined with input from interpreted seismic horizons. The deterministic modification implies either a scaling of the throw, leaving the length of the fault unchanged or increasing/decreasing the throw by a constant which means that a new fault tip line is estimated. Figure 2 illustrates the effect of displacement modifications.
Figure 2: Effect of changing the displacement. In the lower figure, the displacement for the two faults to the left has been increased compared to the upper one. This changes the connectivity between the structural layers significantly.

In both the case of position change and displacement modification, the deterministic workflows are typically used to establish base and min/max scenarios while stochastic realizations are applied in a Monte-Carlo setting to calculate statistical properties. Faults below seismic resolution can be modelled by a stochastic process that distributes smaller faults in the reservoir either through global trends or as secondary faults linked to seismic visible primary faults.

The modelling tool allows for setting up different workflows to analyse the sources of uncertainty one at the time or combined to give a total effect. Examples from a synthetic case based on a real reservoir will be given to show different aspects of the uncertainty modelling.
Analogue Modelling of Inverted Domino-Style Fault Systems

Lydia Jagger, Ken McClay, Fault Dynamics Research Group, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UK

Inversion of pre-existing extensional fault systems is common in rift basins and passive margins and significantly influences the development of hydrocarbon trap structures. In this study the detailed geometric and kinematic evolution of inversion structures developed above reactivated domino-style basement fault systems was investigated using scaled 2D sandbox experiments. Progressive model deformation was monitored using high-resolution time-lapse photography and digital image correlation (DIC) techniques. The resultant detailed strain and particle displacement analyses highlighted reactivated fault evolution as well as hangingwall deformation patterns and enabled the development of new evolutionary models for inversion of domino-style fault systems.

Inversion of domino-style basement fault systems produced characteristic syn-rift harpoon geometries, asymmetric fault-propagation folds and low angle shortcut faults in the footwalls of the main reactivated fault systems. The contractional deformation associated with shortening was dominantly accommodated by footwall-vergent faults. Pre-existing extensional fault architectures and basement fault geometry exerted a fundamental control on inversion styles.

DIC strain monitoring highlighted fault activities and strain evolution during shortening, illustrating complex vertical fault segmentation and linkage as the major faults were reactivated and strain was transferred onto footwall shortcut faults. Detailed particle displacement analysis indicated that progressive hangingwall deformation during extension and inversion was dominated by a significant component of rotation. Hangingwall shear angle varied according to the relative rotation of the hangingwall and footwall blocks and progressively decreased during inversion as the basement faults were back-rotated.

Variations in mechanical stratigraphy strongly influenced fold and fracture development and propagation of the reactivated faults during inversion. In models with mechanically weak layers in the syn-rift and post-rift sequences shortening was dominantly accommodated by folding and vertically segmented footwall shortcut fault systems were developed as the less competent layers facilitated layer-parallel slip. Models with mechanically strong layers in the syn-rift and post-rift sequences produced higher densities of vertically linked shortcut fault and fracture systems which resulted in the development of complex cross-cutting fault systems in the footwalls of the main reactivated faults.

The analogue models show similarities with natural examples of inverted domino fault systems observed in seismic data. Detailed analysis of the model results may therefore be applied to seismic interpretation and understanding of the structural and strain evolution of inverted hydrocarbon trap structures. Understanding hangingwall deformation above reactivated basement faults during extension and inversion is important for the construction and restoration of balanced cross-sections and the physical models can provide insights into the algorithms that need to be applied in restoration software.
How long is a fault? The implications of (not) understanding fault dimensions from seismic data in exploration and production

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It is easy to fall for the temptation to believe that the seismically mapped tipline of a fault represents the line where displacement is zero and the fault actually ends. Yet, all faults in the subsurface have portions that fall below the resolution of any seismic dataset. In this contribution we explore the effects of this sub-seismic fault domain and discuss the implications of appreciating or ignoring it in exploration and production settings. This is done by the use of two examples:

First, we look at an outcrop example, where we study the length and character of the tip zone. We use reservoir modeling and fluid flow simulation to quantify the effect fault tip zone on fluid flow and reservoir compartmentalization. The studied fault exemplifies that the fault tip zone may extend several hundred meters beyond the seismically mapped tip, depending on vertical seismic resolution and fault displacement gradients. The flow simulation results demonstrate that the low-permeable tip zone may generate steep pressure gradients in a reservoir and may affect the tortuosity of reservoir fluid flow. As such, the sub-seismic continuity of seismically mapped faults should not be ignored in production.

Second, we discuss the implications of understanding (or not understanding) fault dimensions in an exploration setting. We do so by applying the lessons of the outcrop and flow simulation example to a real subsurface example where we discuss how this may affect the delineation of fault-controlled prospects. We demonstrate how small adjustments in fault interpretations in the sub-seismic domain may significantly affect trap definition, prospect volumes, project economics and the selection of exploration well locations.

Overall, the results and examples of our contribution highlight the importance of accounting for the fact that faults do indeed continue past the seismically mappable fault tip. Therefore, and finally, we discuss a very simple method for the estimation of sub-seismic fault continuity past the seismically mapped tip.
Session Six: Prospect Scale

Chairs: Clare Bond & Douglas Paton

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New models for fault zones recognize that faults are not simple planar features but are highly complex zones within which displacement and strain are concentrated onto one or several discrete slip surfaces or zones of intense shearing, enclosing variably strained rock volumes. Fault segments and intervening relay zones are a common form of propagation-related complexity which can be observed both in map view and in cross-section on a wide range of scales and for each mode of faulting. Relay zones, the rock volumes between adjacent kinematically related fault segments, are subjected to increasing strains and bed rotations as displacement increases on a segmented fault, eventually causing failure of the relay zone by the formation of a linking fault to form a ‘breached relay zone’. The former relay zone may become incorporated into the fault, initially as a fault-bounded lens and perhaps ultimately as a zone of thickened fault rock, which may be entrained along the fault surface in the displacement direction. Whatever the ultimate outcome of a relay zone, recent work indicates that their presence could have a major impact on fluid flow linked to a number of application areas. In this talk, we briefly review current thinking on the evolution of segmented faults and associated faults, followed by descriptions of a selection of case studies highlighting the different ways in which relays can impact flow in hydrocarbon and minerals flow systems, and how these effects are incorporated in industry workflows, either as conceptual models or as flow modeling solutions.

The impact of relays on fluid flow depends on their scale and the nature of flow system concerned. For example, in fault seal studies of clastic sequences in which faults are detrimental to hydrocarbon flow, the presence of relays on an otherwise continuous sealing fault may provide cross-fault pathways and the absence of a fault trap, but this need not be the case depending on the displacement on the fault and the integrity of the relay. Newly developed techniques provide a basis for quantifying the impact of either individual relays or a population of relays on reservoir production (Fig. 1), and have already shown how case specific the flow implications are: depending on many factors, such as the nature of the faulted sequence or the fault pattern, the flow impact can be insignificant or major. Similarly, relays can have a profound impact on hydrocarbon migration and the development of traps within a region, an issue which is, however, more often considered in qualitative terms, though there are also recently developed flow modeling approaches which could be applied to such problems. By contrast, in flow systems characterized by low-permeability host rocks and conductive fault-related fluid flow, relays can provide the locus for up-fault fluid flow. The inclusion of relay-related flow in so-called fractured reservoirs, such as limestones, is much less routine, partly because of the relatively poor parameterization of these conductive fracture flow systems, but also because of shortcomings in associated flow modeling schemes. Using 3D constraints from Irish Carboniferous Zn-Pb deposits we show that relays can have a profound impact on fluid flow and can be responsible for the formation of world-class mineral deposits (Fig. 2). Our work highlights the benefits of interactions between structural geologists in different application areas on flow-related issues.
Figure 1: Model showing flow paths associated with flow within the top layer (Layer 1) of the hangingwall compartment of a multi-layered, faulted model. The model comprises a layer-cake sequence of permeable and impermeable layers, each three grid-blocks thick— for the sake of clarity, only the central gridblocks of each permeable layer are shown in (A), with grid-block coloured by pressure, normalized to the total pressure difference between the injector and producer well. (B) The middle permeable layer in the model highlights the role of connections across the relay-bounding faults at causing pressure perturbations in other layers. (C) Streamlines deriving from the pressure solver, indicating flow paths in every permeable layer in the model. The model does not contain fault-rock, hence the across-fault transmissibilities are a simple function of the connection area and permeabilities of the juxtaposed layers. Simulation performed using 3dsl from Streamsim. Models are 50 x 69 x 39 grid-blocks representing a 500 m x 500 m x 78 m volume. Fault throw is 20 m. Vertical exaggeration x10 throughout. From Manzocchi et al. 2010, Geofluids, 10, 94-113.

Figure 2: Map showing the segmented faults (red) associated with the Lisheen Zn-Pb mineral deposit in Co. Tipperary, Ireland. Relays occur on 3 different scales with the distribution of Zn-Pb linked to 3rd order relays.
Basement-Related Transfer Faults or Lineaments in the Faeroe-Shetland Basin: A New Insight from Analysis of 3D Data from the Muckle Sub Basin.

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A 3D seismic survey from the Muckle sub-basin has been used to investigate the segmentation of the eastern part of the Faeroe-Shetland basin on the NW European margin. The Faeroe-Shetland basin is an extensional basin segmented by series of NW-SE oriented basement-involved structures – postulated to be transfer fault systems. These features appear to have played an important role in the evolution of the basin and in particular as sediment input points into the rift system. In this paper a basement-involved transfer zone model is invoked for the along-strike segmentation of the basin. Structural interpretations of the 3D dataset indicate such a basement-related transfer zone model. These features are –

(i) Structures that show lateral dextral offsets within the area of study;
(ii) Narrow, linear erosive valley systems from 2 to 10km wide that are aligned NW-SE above inferred basement transfer fault systems – these valleys form Jurassic to Paleocene sedimentary entry points into the basin;
(iii) Alignment of dykes and sill complexes along these inferred transfer zones;
(iv) Reactivation features along the inferred transfer zones;
(v) Complex deformation of basement rocks between transfer zones implying movement of deep crustal faults.

The seismic data show variable degrees of fault reactivation across the study area indicating that not all the transfer systems were reactivated from the Devonian to the Early Palaeocene. Key to identifying the basement-involved transfer systems are –

(i) Recognition on gravity and magnetic maps;
(ii) Mapping displacements in cross-sections and on time-structure maps;
(iii) Recognition of their control on sediment input points – usually indicated by narrow linear valleys at high angles to the rift trend;
(iv) Localisation of sill and dyke systems along these features.

Analogue modelling of transfer structures in rift systems has produced similar features to those found in the Faeroe-Shetland basin system supporting the transfer zone model for basin segmentation.
Crustal extension during volcanic margin formation is typically accommodated via a two-stage process dominated first by mechanical faulting and then by magmatic intrusion. Numerous field and sub-surface studies have demonstrated that pre-existing fault networks may facilitate the later emplacement of magmatic complexes by providing relatively low-permeability magma flow conduits. While fault-hosted igneous intrusions may therefore influence fluid migration pathways, fault seal potential, trap formation and strain partitioning during magmatically-assisted rifting, the degree of and controls on the interaction between normal faults and magma intrusion remain unclear.

Here, we use high-quality 3D seismic reflection data from the Exmouth Sub-basin, offshore NW Australia, to quantitatively describe the geometrical relationships between a rift-related normal fault array and several saucer-shaped sills. The Exmouth Sub-basin is located in the Western Australia volcanic margin and formed during the Mesozoic in response to two discrete rift events. The second rift phase occurred during the Berriasian and was characterised by the formation of a dense, conjugate fault network that influenced the architecture of a later (Early Cretaceous) mafic magmatic system (Fig. 1). We primarily focus on ‘Sill A’ (Fig. 1), which detailed mapping indicates has a saucer-shaped morphology and consists of a strata-concordant, inner sill (c. 2 km radius) that passes laterally into an inclined sheet (c. 300 m high) (Fig. 1D). Seven faults associated with the sill dip eastward at 25–30° and often display corrugated fault traces with average wavelengths of 2 km and amplitudes of c. 100 m (Fig. 1E).

![Fig. 1](image-url)
The relationship between the faults and the sill can be characterised by three fault-intrusion inter-relationships (Fig. 2): (1) the sill cross-cuts and is not offset across the fault, indicating that emplacement occurred after the main rift phase (Fig. 1A); (2) there is a small ‘step’ (c. <100 m) in the sill, with a long axis parallel to the fault, between the hangingwall and footwall (Fig. 1B) or (3) an inclined segment of the sill has the same dip as and appears to be intruded into the fault (Fig. 1C).

We suggest that where the sill is concordant and cuts directly through a fault, it is likely that two separate but mechanically similar juxtaposed lithologies have been intruded (Fig. 2A). In contrast, step development along faults appears to be related to increases in the offset of preferentially intruded horizons. For example, in Figure 2A we suggest that a SE-propagating step, unrelated to a fault, was ‘captured’ by a fault due to the offset across the fault of horizons that could be preferentially intruded. This likely resulted in a reorientation of the magma flow direction to parallel to fault strike. These observations suggest that the pre-intrusion fault seal potential influence emplacement dynamics.

Fig. 2 – Schematic diagrams highlighting the possible relationships between sill components and a fault.

Inclined sheets that appear to intrude faults are commonly laterally restricted and transgress for c. 300 m up the fault (Fig. 1C). Figure 1E shows that these areas intrude fault sections characterised by a positive fault-plane corrugation (i.e. the footwall has a convex geometry that points in the fault dip direction). Reconstructed magma flow directions for the sill are often oblique to fault strike, implying that magma was locally redirected to flow up the faults. Such an abrupt rotation in the magma flow direction may have been related to a change in the orientation of the local principal stresses, possibly resulting from the interference between an intrusion-induced stress field and near-fault stress field variations associated with a positive fault-plane corrugation. We suggest that the rotation of \( \sigma_3 \) from a sub-vertical (i.e. typical of sill intrusion) to a steeply, westward-dipping (~70–80°) orientation in the vicinity of the positive corrugations favoured the intrusion of suitably oriented faults rather than continued bedding-parallel intrusion (Fig. 2B).

Our observations suggest that the pre-existing normal fault array significantly influenced the morphology of Sill A through: (1) the juxtaposition of stratigraphic units with varying mechanical properties and (2) by providing suitably oriented pre-existing fractures that were reactivated as magma conduits where positive fault-plane corrugations altered the orientation of the principal stress axes. Importantly, sill transgression up fault dip only occurs along areally restricted positive footwall corrugations. This implies that fluid migration pathways may only be locally influenced as magma intrusion appears to be constrained to specific fault segment geometries. Furthermore, this suggests that fault strength (i.e. fault-plane hosted intrusions likely increase the cohesion and angle of internal friction of a fault) and strain-partitioning is non-uniform along fault-strike; a characteristic that may affect the distribution and dynamics of subsequent fault-plane reactivation.
Session Seven: Prospect Scale

Chairs: Matthew Allen & John Karlo
Structural Controls on the Preservation of Pre-Rift Stratigraphy in the North Red Sea, Egypt

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This study comprised an integrated structural re-interpretation of the offshore Northern Red Sea, Egypt following the completion of the Hess operated North Red Sea 2A well. We have utilized a combination of seismic, well and field data to explain stratigraphic patterns observed in offshore wells. As in the Gulf of Suez, the North Red Sea contains a hydrocarbon play involving Late Cretaceous to Eocene pre-rift strata, which provide both oil-prone source rocks and various potential reservoir units. In the North Red Sea, however, the pre-rift play has so far proved to be elusive in offshore exploratory drilling. Although numerous geochemical indicators from offshore wells point to the presence of a mature pre-rift source rock, it is only in the onshore that the source rock has been directly sampled. In the offshore, the pre-rift strata have typically been absent due to erosion at the locations targeted by exploration wells. This study provides a structural model to help explain the erosional patterns observed in offshore wells. Offshore seismic data quality is insufficient to discriminate pre-rift from younger sequences, but does provide insight into the extensional fault geometries and regional structural fabric. Seismic interpretation reveals two major normal fault trends offshore, oriented NNW-SSE and WNW-ESE respectively. Correlation of detailed biostratigraphic zones in offshore wells has provided constraint on the timing of the faults. First active are: the NNW-SSE oriented faults that are related to early Miocene rifting. The WNW-ESE faults oriented faults are active in Late Miocene time and overprint the earlier extensional fabric.

We present a structural model where the preservation of pre-rift stratigraphy is controlled by footwall uplift and erosion within the early Miocene normal fault system. This pattern is modified in the Late Miocene by a phase of NE-SW extension. Structural reconstruction of the late Miocene fault movements allow the original early Miocene fault array to be restored. Doing so reveals that the pre-rift erosion profile is related to along-strike throw profiles on the early Miocene faults. The likelihood of pre-rift preservation on footwall traps is least at throw maxima (where footwall uplift is greatest) and preservation likelihood progressively increases off-structure towards the fault tips. Similar erosion patterns are present in onshore outcrops, for example within the Hammrawen fault block, near Quesir, Egypt. There it is apparent that syn-tectonic erosion and removal of pre-rift strata is related to fault timing and throw magnitude, thereby providing a predictive model for the locations of preserved pre-rift strata in the Northern Red Sea. Given the critical role that the pre-rift plays in the petroleum systems of the North Red Sea, our structural model has implications for remaining prospectivity controls in the study area.
Kinematic Indicators of Strike-Slip Faults in 3D Seismic Data: Implications for Fault Propagation

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A kinematic indicator is a geological structure or feature that can be used to identify both direction and magnitude of translation, in this case providing measurable piercing points for strike-slip fault offsets. We document for the first time a set of stratigraphic and structural kinematic indicators based on three-dimensional (3D) seismic reflection data. Stratigraphic types include any uniquely recognizable sedimentary feature such as meandering deepwater channels (Fig. 1), and grooves left by large intact blocks within internally disaggregated mass transport deposits. Structural indicators include the systematic offset of older intersecting faults (Fig. 2).

The examples presented here come from the deepwater Levant Basin located in the Eastern Mediterranean. This area reveals a complex network of conjugate strike-slip faults that propagated in the last two million years due to gravity driven salt tectonics. The faults are part of a contractional structural assemblage in the down-dip toe domain of the gravity linked system and detach at the Messinian evaporites. Using seismic attributes such as coherency and dip-maps, the plan view geometry of these strike-slip faults is revealed across a c. 2km thick clastic overburden overlying the Messinian evaporites. This provides a unique opportunity to map kinematic indicators at points not only along strike of the faults but in depth as well, resulting in a full 3D visualisation of the fault.

The improved views of strike-slip faults in 3D enable us to analyse their evolution. Specifically, by studying the displacement distribution changes on a strike-slip fault, we can better understand how the growth of precursor structures (such as R shears and en echelon normal faults) relate to the growth of the main through-going strike-slip fault zone. This will not only improve our insight into strike-slip fault propagation, but enable further investigation into how fluid flows in these systems, thus improving success in future hydrocarbon extraction.
Figure 1: Coherency slice showing a group of mostly sinistral faults (shown in red) that have clearly offset deepwater channels in this region. The fault network comprises offsets from less than 100m on smaller splay faults in (c), to over 1km of offset on the larger fault in (d). This allows for further analysis into splay relationships with the master faults.

Figure 2: A coherency slice showing a dextral strike-slip fault and its splay (in yellow) that have been offset by a sinistral fault (in red) by 130m and 120m, respectively. The levee scarps of a meandering channel are also present and although difficult to correlate exactly, show that offsets from the fault are similar to those of the channel.
Integrating Digital Mapping with Constrained Model Building and Structural Validation

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The use of geological modelling software is commonplace in many exploration groups in the resource industries, but few of the models built using such software are tested to identify geological uncertainty. Validation software offers great potential to reduce risk in geological models used at all stages of the exploration cycle. Reducing risk in geological models requires tools that use geometrical constraints which are based firmly on sound geological concepts.

In onshore exploration areas, model building often begins with data collected during field mapping. When field mapping is done digitally, with the right software tools, the user benefits from all the advantages of working with geospatial data yet loses none of the benefits of traditional paper mapping. FieldMove aims to replicate and enhance the traditional paper mapping experience and is designed to run on rugged tablet PC’s. It provides the flexibility to work at multiple scales in one project. Digital mapping removes the potential for errors when generating a “fair copy” map as there is no need to prepare it separately, allowing the user to directly start data analysis during the field campaign.

Structural integrity of a cross section, or of a 3D model is facilitated greatly by using rule-based model building. Data collected during digital mapping can be integrated in 3D and simultaneously visualised in map, section and 3D views. Direct access to tools for cross-section construction and 3D model building allows geometrically plausible models to be built rapidly during the field campaign.

Once a model has been built, validity can be tested using kinematic modelling, further improving accuracy, reducing uncertainty and substantially reducing risk. Validation encompasses a range of techniques such as line-length and area balancing. Geological models can also be tested using a series of deformation algorithms which allow full sequential restoration and forward modelling. This gives predictive insight into the geometries and linkages of the fault framework through time with implications for the relationships between the petroleum or mineralization system and structure.

An example of digital mapping with constrained model building and structural validation will be presented from Mt. Lykaion, Sanctuary of Zeus, in Greece.
Mt. Lykaion model shown simultaneously visualized in map, section and 3D view in Move. Updates on one view are automatically applied to the other views, this interface provides a real advantage when analysing the data to gain an understanding of the structural geology and tectonic history of an area.

Constrained (rule-based) cross section construction. An example is shown of horizons constructed from a template using the dip isogon method in Move. Dip isogon construction allows for variation in rock behaviour between layers and allows the construction of any of the fold styles in the Ramsay classification.
Fracture Characterisation in Crystalline Basement: Building an Analogue for the Clair Basement Based on the Lewisian Gneiss Complex of NW Scotland

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Fractured basement reservoirs, like all unconventional hydrocarbon plays, seem set to be an increasingly attractive prospect for energy companies as conventional oil and gas reservoirs are preferentially exploited and depleted. Basement is often vaguely defined but here we use the definition of Landes et al. (1960) that it is ‘any metamorphic or igneous rock (regardless of age) which is unconformably overlain by a sedimentary sequence’. Motivation for this study was provided by the Clair Oil field, located 75 km west of Shetland. The primary Clair reservoir is situated within Devonian and Carboniferous fluvial/lacustrine sediments that overlie and onlap a topographic basement-cored high, the Rona Ridge of Late Archaean to Early Proterozoic granodiorite/diorite/granitic gneisses and pegmatites. Well tests from the basement and from the overlying sediments suggest that there must be fluid pathways through the basement (Falt et al., 1992, Coney et al., 1993) connecting sedimentary packages across the main ridge structure, and that fracture systems within the basement may also provide significant storage space for hydrocarbons. Thus a key role for fractures cutting basement gneisses is becoming increasingly recognised as the field is being developed.

In this study, we present 3D fracture network characteristics of basement rocks of NW Scotland. These have been analysed and quantitatively compared to assess their suitability as an analogue for the fracture networks within the Clair basement. Onshore datasets (outcrop, terrestrial laser scans & NEXTMap\textsuperscript{\textregistered} DEM) from mainland NW Scotland exhibit prominent NE-SW and/or NW-SE fault and fracture trends (Fig. 1). Fracture spacing distributions from the mainland LGC are well described by power-law relationships at scales that span five orders of magnitude. Similar power-law relationships are also indicated from the Clair basement datasets however the limited numbers and scale range of structures observed means that these relationships are much less well constrained.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fracture_characterisation.pdf}
\caption{Onshore datasets from the Lewisian Gneiss Complex from Scottish mainland. a) Linements picked on NEXTMap data, b) Outcrop-scale fracture dataset locations, c) Lidar (Terrestrial laser scan) derived 3D fracture networks}
\end{figure}
The Outer Hebrides show different primary fracture orientations, with those on Lewis and Harris displaying strong NNW-SSE and ENE-WSW trending fractures (Fig. 2). Relative age dating of these fractures using the Permo-Triassic Stornoway Formation demonstrates they are of similar age to important open fractures at the Clair Field, with multiple phases of faulting in the basement of the Outer Hebrides producing very similar fault rocks to those seen at Clair. Large seismic-scale Mesozoic faults in the Lewisian of Lewis and Harris are accessible. An additional finding here is that in directions perpendicular to the fault plane fracture spacing is described by power law, whereas parallel to the fault plane, fractures exhibit a random fracture spacing distribution attributable to jointing and a background level of fracturing present in the gneiss.

This work has shown that the LGC in the mainland and Hebrides is a suitable analogue for the Clair basement ridge, however there are important differences to account for when building an analogue model. The Clair basement seismic dataset exhibit comparable NE-SW & NW-SE trending faults to mainland Scotland, however basement core samples exhibit a strongly aligned NNE-SSW fracture trend that is not clearly represented in the onshore datasets. Faults and fractures on Lewis and Harris have different orientations to Clair (and the mainland) but are of similar age and contain similar fault rocks to the offshore field. The mainland fault rocks are not similar to Clair and are likely to be of differing ages. The onshore data provide a range of model types that can be used in sensitivity models to ultimately assess which onshore dataset provides the best geological and statistical analogue for the Clair basement.

Figure 2. a). Fracture patterns on Lewis and Harris and b) study locations

The observations, analysis and discussions that have taken place during the course of these projects and associated industry fieldtrips have been used by the industry sponsors (Clair Joint Venture) to better understand the Clair basement fracture network potential and improve the geological models for the Clair Field as a whole. This in turn fed-in to the Clair co-venture’s economic re-assessment of the Clair field. The newly constrained geological model and the improved economic assessment mean that the Clair Ridge project (Clair Field Development - Phase 2) has recently been sanctioned for development resulting in an investment of approximately £4.5 billion into the UK economy.
Absolute age dating of faulting using rhenium-osmium (Re-Os) geochronology in ore deposits and hydrocarbon basins

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The reactivation of continental fault zones is a widely recognized phenomenon and is generally indicated by the presence of multiple overprinting sets of ductile and/or brittle fault rocks. Whilst it is relatively straightforward to establish the relative ages of the different fault rocks present using cross-cutting relationships in the field and thin section, the absolute dating of fault rock formation events has remained an enduring problem due to a lack of material suitable for most radiometric techniques. Further the origin of the fluids that migrate through faults is also challenging to identify.

Fault zones are commonly associated with the precipitation of quartz, calcite and sulphide minerals, e.g., pyrite and, to a lesser extent, chalcopyrite and molybdenite. These sulphide minerals are commonly enriched at the parts per billion (million for molybdenite) level with rhenium (Re) and, through the radiometric decay of $^{187}\text{Re}$ to $^{187}\text{Os}$, permits the application of the $^{187}\text{Re}-^{187}\text{Os}$ geochronometer to date the timing of mineralization and by inference the absolute timing of fault movement and/or reactivation. Thus the combination of structural evidence and Re-Os geochronology yields an accurate understanding of the absolute chronology of fault movements and associated mineralisation.

The Re-Os pyrite (sulphide) system has the capability to not only yield the absolute age for fault movements and/or reactivation, but also to provide evidence on the origin(s) of the fluid that migrated through the fault. The latter is achieved by utilising the $^{187}\text{Os}/^{188}\text{Os}$ composition of the sulphide at the time of formation, which is determined by Re-Os geochronology. As an illustration of the potential of the technique we report Re-Os sulphide geochronology from both fracture-hosted ore deposit (Lupa Goldfield, Tanzania, Assynt Terrane, Scotland) and hydrocarbon (West of Shetland oilfield) systems.

The Lupa goldfield comprises a series of greenschist-facies brittle-ductile shear zone-hosted gold occurrences. The mineralized fault systems are typical of the orogenic Au deposit type and are situated within a Paleoproterozoic magmatic arc that has intruded the Archean Tanzanian cratonic margin. Molybdenite and pyrite ages established for the mineralized fault zones and within oblique-extension veins are broadly equivalent (e.g., 1886 ± 6 Ma; n = 4; 1894 ± 45 Ma; n = 2; 1885 ± 9 Ma; n = 9; 1905 ± 25 Ma; n = 2). These Re-Os ages are also consistent with a pyrite Re-Os age from the mylonitic shear zones associated with the Lupa goldfield (1884 ± 15 Ma) which envelope fault-fill veins and constrain the timing of mylonitization. Thus the Re-Os ages show that the sulphides from five shear zones are broadly contemporaneous suggesting that the mylonitic shear zones are an interconnected network of mid-crustal permeable fluid conduits at ca. 1885 Ma that permitted the transportation and deposition of gold.

A set of previously unrecognised quartz-pyrite veins are present in the Assynt Terrane of the mainland Lewisian Complex, northwest Scotland. These veins cross-cut early (ca. 2.9-2.8 Ga) Badcallian gneissose fabrics, (ca. 2.4 Ga) Scourie dykes and early pre-dyke fabrics related to the Inverian shearing event. They are then overprinted and reworked by Laxfordian deformation (ca. 1.8 Ga) and by later brittle faults of various ages. The veins represent a multi-modal system of tensile/hybrid fractures that were influenced by the existing foliation of the gneisses. Pyrite Re-Os dates of 2259 ± 61 Ma confirm the regional chronology and provide the
first reliable constraint for the Inverian, the main shear zone forming event in the Lewisian Complex.

The Clair oil field is one of the largest oil fields in the UK sector and is forecast to produce until 2050. Part of the Clair field reservoir comprises fractured Lewisian basement. Therefore knowing the timing of fracture formation is key to estimating the timing of oil migration. Two core samples from the Clair oil field comprising fractured Lewisian basement infilled with pyrite, calcite and bitumin were investigated. Pyrite predates the oil within the fracture. The pyrite contains low abundances of Re and Os with the Re-Os isotope compositions that are similar to yield an isochron. In contrast, the bitumen associated with the pyrite is enriched in both Re and Os (~16 ppb Re ~800 ppt Os). The osmium isotopic values of both the pyrite and bitumen, when calculated at the time of oil generation (68 ± 13 Ma) are similar to those of published oil data from the Clair field ($^{187}\text{Os}/^{188}\text{Os} = ~1.0 ± 0.2$). Regression of the published Re-Os data with the new pyrite Re-Os data forms a more precise generation age of 72 ± 5 Ma and the bitumen associated with the pyrite produces a generation/migration age of 64.4 Ma. The new Re-Os dates, not only confirm the oil generation age of the Clair field, but also provide a minimum age of fracturing within the basement of 72 ± 5 Ma.

Sulphide mineralisation occurs in fault and fracture (hydrocarbon) systems worldwide and the application of Re-Os geochronology can yield valuable constraints on the timing of faulting and mineralisation in the crust. These absolute age constraints will be of substantial value to the global mining and hydrocarbon industry.
Session Eight: Uncertainty, Risk, Value

Chairs: Matthew Allen & John Karlo
Keynote Presentation: Structural Controls on Pressure and Influences of Pressure on Structure

Richard Swarbrick, Global Director, Ikon GeoPressure, Durham

Knowledge of subsurface pressures is critical to safe drilling, as well as to understand elements of petroleum migration and trapping. Pressures above “normal” (captured numerically by estimating overpressure), are generated by a variety of mechanisms, some operating only during deep burial at elevated temperatures. To retain the overpressure in high-permeability reservoirs requires isolation of the reservoir, frequently involving faults as seals. Conversely faults and fractures can act as high-speed fluid escape paths. Success in pressure prediction prior to drilling involves understanding of basin architecture, knowledge of reservoir and seal distributions, and estimation of stress and strain histories. Extreme high pore pressures can reach the fracture pressure and create conditions for tensile failure leading to breaching of the seal. Seal breach risk analysis should form part of pre-drill assessment in high pressure regions such as the North Sea and Mid-Norway. To evaluate such conditions requires estimation of pore pressure – fracture gradient (PPFG) coupling, which also creates challenging conditions for drilling through naturally regressed and/or depleted reservoirs. Regional mapping, combining pressure data with structure maps based on seismic interpretations, reveals over 100 pressure cells in the Upper Jurassic section of the Central North Sea, compared to a principal fault system in similar aged rocks in Mid-Norway which separates high and low overpressure regions. Comparison of the pressure histories will be discussed and implications for hydrocarbon trapping.
Constraining the Question - Addressing Uncertainties in Industry Data without Trying to Reduce the Irreducible

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Uncertainty is a fundamental element of science, and geological sciences are far from exempt in the amount of uncertainty involved. Interpretations of sub-surface geology are often based on 1D well data, in combination with remotely sensed information. The scarcity of ‘hard physical’ data in combination with the limited resolution of remotely sensed information provides a key challenge for the industrial geologist exploring for resources. Creating an interpretation of sub-surface geology extends from defining the broad geometries, the main units and their structural configuration; to populating this model with the physical and chemical characteristics of the defined units. Structural geology skills are at the heart of this process, from identifying physical discontinuities, faults or shear zones; to understanding how the physical properties of the rocks will behave. For example, under pressure increases or decreases, as fluids are injected, or oil and gas produced; to understanding how fluids will be controlled by fractures during mineralization, production of shale gas and/or whole rock permeability for EOR.

The uncertainties in geologists’ predictions are insurmountable, as demonstrated by oil and gas exploration success rates as low as 20% (Loizou, 2002); providing a cautionary example of the uncertainties involved for the industrial geologist. The need to accept a significant irreducible uncertainty is true across geology and improving understanding of uncertainties, how to communicate them, and how to practically deal with uncertainty, whilst getting on with the job, are all key (but under-valued?) skills of an industrial geologist. This paper will highlight recent work on uncertainties in geology, with particular reference to structural geology; the methods used to elicit and reduce uncertainties in geological interpretation; the influence of media and public perception; and perhaps most importantly how to frame the questions to ask to address uncertainties without trying to reduce the irreducible.
Collaborative links between universities and industry are unquestionably mutually beneficial. In particular this link can be invaluable where either ‘blue-skies’ science can be applied to more practical uses or where a broader understanding of a topic can developed through an integrated or longer term study. In this contribution we provide examples of both of these from the Basin Structure Group Joint Industry Project.

We should, however, be mindful that the collaborative link is more complex than that. Often non-applied academics consider industry is getting work done on the cheap and is not ‘proper’ science; conversely within industry there can be a perception that research should only be funded if it directly (and demonstrably) adds to the bottom line of a specific asset.

As academics we need to be aware that our science is being funded broadly for business needs and deliverables need partly to align to that. Industry needs to be aware of the wide range of pressures on the universities, especially within the applied side. Substantial changes in student dynamics with the advent of undergraduate fees and withdrawal of NERC funding for Taught Postgraduate MSc will no doubt alter the graduate recruitment scene over the next couple of years. Within Structural Geology specifically the number of places teaching advanced level structural geology is limited which limits the opportunity to enthuse students about the subject at the graduate as well as reduces the number of students with the specific skills needed. This impacts industry recruitment but also industry research as the availability of students interested in Structural Geology PhDs reduces. Over the coming years this will compound the shortage of industry structural geologists.

Two further constraints are important. With the forthcoming Research Excellence Framework exercise the quality of research output will be assessed and there continues to be a debate over the value of an applied paper compared to blue-skies paper, even if this REF will include an impact component. Secondly, Funding Councils support for applied research is increasingly scarce making it necessary for more companies to dig deep and pay for research. Collaboration is, therefore, critical but both industry and academia need to think (and discuss!) not just about that next PhD project but the longer term requirements from both perspectives.
What Value is Structural Geology to the Petroleum Industry?

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Perception of the value of Structural Geology in the Petroleum Industry varies widely. Our intent is to offer a framework for considering the value of Structural Geology in Exploration and Production. These ideas may help lead into the discussion session in the Conference.

Hydrocarbon Exploration and Production is a commercial activity where value is ultimately measured in terms of monetary worth. At current oil prices global production represents some 3 trillion dollars per year of activity. Structural Geology features – or could do – in many if not all of the exploration and reservoir management projects that underpin this output. Measuring the value of individual pieces of technical work can be subjective and quantifying the impact of a technical discipline on an entire industry is difficult. But we identify examples where Structural Geology is directly impactful for example generating prospects or determining well locations. We also identify scenarios of indirect value for instance workflow efficiency.

Structural Geology activity in the Petroleum Industry has changed through time. Early days were dominated by fieldwork; today Structural Geology features in a diverse set of activities largely executed on office-based computer workstations including reflection seismic interpretation, image log interpretation and geomechanics. Some of these activities can be regarded as sub-disciplines in their own right, such as structural model validation and wellbore stability analysis. Other applications could be regarded as part of general Petroleum Geoscientist skillsets for instance accurate representation of structural style in seismic interpretation.

Subsurface mapping and workflows increasingly recognise the importance of uncertainty. Structural Geology plays a key role in probabilistic descriptions for example fault position or seal probabilities and structural style uncertainty. The principles of Structural Geology also help combat subsurface model bias.

Most subsets of applied Structural Geology activity have routine and specialist aspects. For example defining the structural elements in a conventional reservoir description is clearly a general Petroleum Geoscientist skill, but predicting fracture permeability sweet spots is a specialist or even research activity.

The value of Structural Geology in the Petroleum Industry is large because Structural Geology defines the multiscale geometrical and mechanical framework that encompasses the Exploration through Production phases of any subsurface project. In many organisations there may be opportunity to emphasise Structural Geology capability in terms of training offers for generalist staff, and making best use of in-house and external specialists and researchers to leverage available workflows and technologies.
Friday 30 November

Session Nine: Development, Fractures and Geomechanics

Chairs: Richard Fox & Paul MacKay
Keynote Presentation: Estimating Fracture Network Properties from the Confines of a Well

David J Sanderson\textsuperscript{1,2}, Sebastian Turner\textsuperscript{2}

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The properties of rocks containing fractures and other discontinuities (including faults, deformation bands and stylolites) can be attributed to both the attributes of the fractures (orientation, size and other physical properties) and the network topology (i.e. the arrangement of fractures to one another). For some attributes, such as orientation and thickness (aperture) it is relatively easy to produce unbiased estimates from core or image logs, for others, such as size and connectivity, it is extremely difficult.

The geometry and topology of fracture networks have been studied in terms of a system of branches and nodes. Nodes represent the tips of fractures (I-nodes), or where fractures abut or cross one another (Y- and X-nodes, respectively), with branches connecting the nodes. The proportion of different types of nodes or branches can be used to define the number of lines and branches, and to classify the topology of fracture networks, using a system developed by Manzocchi (2001)*.

One important property of the network is its connectivity, which is shown to depend on four features: 1) the number and relative orientation of fracture sets, 2) the fracture intensity (units m\textsuperscript{-1}), 3) the characteristic size of the fractures (m), and 4) the topology of the network. The fracture intensity and characteristic size can be multiplied together to define a dimensionless parameter, In 2-dimensions, this can be evaluated for either fracture traces or branches. Branches provide unambiguous measures, with smaller and more tightly constrained length-scales, that may be used to define measures of fracture connectivity, especially suitable in the confined volume of a well.

Using results from the study of both lattice and continuum percolation, it is possible to determine the dimensionless branch intensity at which a spanning cluster will develop in networks of various topologies. The extension of these results to 3-dimensional networks will be discussed.

These concepts will be discussed with respect to networks of deformation bands (or granulation seams) developed in various wells from offshore Azerbaijan. The results will be compared with onshore analogues and the impact of the deformation band networks on reservoir properties discussed.
Simulated Hydrocarbon Production across Outcrop-Derived Versus Seismically-Resolvable Faults


Structural geometry is a key uncertainty in subsurface geological modelling. Precise fault-horizon intersections, fault zone complexity and fault linkage geometries are often difficult to resolve using seismic data due to effects such as amplitude deterioration and diffraction. This inevitably leads to simplification of structural models when compared to geometries observed in analogous outcrop datasets. In production settings this simplification leads to inaccurate representations of cross-fault reservoir juxtapositions and calculation of the associated fault plane properties, with potentially serious implications for the simulated production response.

To quantify the difference in production across fault geometries typically resolvable in seismic data, and geometries observed in outcrop we have employed the technique of seismic forward modelling. High resolution LiDAR data is used to create a digital elevation model (DEM) capturing the complex fault geometries observed in the Afar rift, Ethiopia. These faults are geologically young, having formed within the last 2 Ma (Rowland et al, 2007), and as a result the original fault geometries are largely preserved. The DEM is used to create a number of detailed fault models and geo-cellular grids which are subsequently populated with a range of petrophysical properties typical to hydrocarbon reservoirs. Ray tracing software (Gjøystdal et al, 2007) is then used to generate synthetic 3D cubes of the seismic response expected for the property distribution represented by these grids at typical North Sea reservoir depths. These cubes are then interpreted, and second geo-cellular grids built and populated based on the seismically resolvable fault geometries. Geologically derived high-, medium- and low-case fault transmissibility multipliers (TMs) (Manzocchi et al, 1999) are calculated prior to simulation of both the outcrop-derived and seismically resolvable-grids.

Comparison of the simulation results allows us to identify instances when disparities between realistic and seismically resolvable fault geometries lead to significant variations in the simulated across-fault flux. One such example is shown in figure 1, where a reservoir interval slightly thinner than the average fault throw is modelled. In this case the complex fault geometry present at outcrop results in significant partitioning of throw across a number of slip planes, allowing numerous cross-fault reservoir:reservoir juxtapositions to be maintained. In contrast, the geometries resolvable in the forward modelled seismic volume consist of simple, single slip planes, hence a limited area of reservoir self-juxtaposition is maintained. During simulation the numerous potential flow pathways across the outcrop-derived geometry result in limited differences in production between the different TMs. Conversely the restricted flow pathways present in the seismically resolvable geometry lead to significant differences between the high-, mid and low case TMs.

Seismic forward modelling allows us to derive the seismic response generated by realistic fault geometries, with significant variations between outcrop and seismically resolvable geometries being observed. The lower complexity of seismically resolvable geometries often leads to lower areas of across-fault self-juxtaposition of faulted stratigraphy compared to their realistic, outcrop-based counterparts. In turn the number of potential flow pathways are reduced, resulting in the across-fault flux being highly influenced by variations in TMs. In contrast, the fault zone complexity observed in outcrop leads to larger areas of across-fault self-juxtaposition, with the TMs consequently being less important in controlling variations in cross-fault flow and production rates. In fields where the throw of intra-reservoir faults approximates the reservoir thickness, the seismically resolvable fault geometry may lead to faults being modelled as being significantly more compartmentalising than is actually the case.
Acknowledgements
We would like to thank Shell for financial contribution to this work, and Schlumberger and NORSAR for access to academic software licenses.

Figure 1. Plot of production rate and cumulative production over a 12 year simulation run for low-, mid- and high-case TMs (left) and water saturation at final timestep for mid-case TMs (right). (A) Outcrop derived fault geometry. The complexity of the fault allows numerous across-fault reservoir:reservoir juxtapositions, and hence potential flow pathways, to be maintained, leading to similar production results regardless of the TMs used. (B) The seismically resolvable fault geometry is considerably less complex than the outcrop geometry, leading to limited areas of reservoir self-juxtaposition. These small juxtaposition ‘windows’ control the across-fault flux, the magnitude of which is significantly dependent on the fault TMs.
Invited Speaker: An Integrated Tensorial Approach for Characterising Fractured Rocks

David Healy, Department of Geology, University of Aberdeen, Aberdeen AB24 3UE

Fracture networks can play a critical role in the safe and efficient management of fluids in fractured rock. Based on previous work by Oda, this presentation develops an integrated tensorial approach to quantifying fracture networks and then predicting some of the key properties of fractured rock: permeability and elasticity (seismic velocity). Each of these properties can be represented as tensors, and these entities capture their essential ‘directionality’, or anisotropy. In structural geology, we are familiar with using tensors for stress and strain, where these concepts incorporate volume averaging of many forces (in the case of the stress tensor), or many displacements (for the strain tensor), to produce more tractable, and more computationally efficient, quantities. It is conceptually attractive to formulate both the structure (the fracture network) and the structure-dependent properties (permeability, elasticity) in a consistent way with tensors of 2nd and 4th rank, as appropriate.

Examples are provided to highlight the interdependence of the property tensors with the geometry of the fracture network. The fabric tensor (or orientation tensor of Woodcock) describes the orientation distribution of fractures in the network. The crack tensor combines the fabric tensor (orientation distribution) with information about the fracture density and fracture size distribution. Refinements to the fracture network, manifested in the values of the fabric and crack tensors, translate into changes in predicted permeability and elasticity (seismic velocity). Such changes may originate from better mapping or better measurements. Turning that around, measured changes in any of the in situ properties or responses in the subsurface (e.g. permeability, seismic velocity) could be used to predict, or at least constrain, the fracture network. Explicitly linking the fracture network geometry to the permeability and elasticity (seismic velocity) through a tensorial formulation provides a useful and efficient alternative to existing models for subsurface characterisation.

Figure 1. Lower hemisphere stereonet projections of the fabric tensor (N), crack tensor (F), permeability tensor (k), and seismic velocity anisotropy (Vp, ΔVs and S1) for a given fracture pattern. Percentages describe the degree of anisotropy.
A new mechanical modelling approach to predict fault and fracture density and connectivity in a mechanically layered sequence

Michael Welch¹, Russell Davies², Rob Knipe¹

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The density and vertical connectivity of faults and fractures are key controls on fluid flow through tight reservoirs. This is particularly the case in mechanically layered reservoirs, where the faults and fractures may be layer-bound, restricted within more brittle layers, or cut through the entire section. The fault and fracture density is a control on the horizontal permeability within individual layers, while the vertical connectivity of faults and fractures between different layers is a control on vertical permeability within the section.

The density of layer-bound faults and fractures depends on a number of factors, including the thickness of the layer, the mechanical properties of the layer and the horizontal strain at the time of fracturing. The vertical connectivity of the faults and fractures depends on the sequence of fault nucleation and propagation across the layers. We have developed FaultProp, a mechanical model of fault nucleation and propagation through a mechanically layered section based on the Griffith energy balance model of dilatant fracture propagation, which is used to estimate the connectivity of faults and fractures between different mechanical layers. By comparing the heave or aperture of individual faults and fractures with the horizontal strain at failure, we estimate the density of layer-bound fractures in the different layers.

This model has been successfully applied to model mapped fractures and faults in a mechanically layered section in outcrop from Price, Utah. This section comprises interbedded ductile shales and brittle tight micrite layers, typically 20cm-2m thick. The brittle micrite layers contain a high density of closely-spaced, layer-bound vertical fractures. However the entire section is also cut by several larger faults with displacements of up to 7m. The mechanical model shows a sequence of fault nucleation and propagation in this section as a function of increasing horizontal strain consistent with the observations.

The value of this model is its application in predicting fault and fracture geometry based on a mechanical stratigraphy derived from wireline log data. This is obviously of value in analysing fracture and fault development in subsurface reservoirs. We will show an example from the Brent section of the Norwegian North Sea where we use wireline logs to calculate mechanical properties and subdivide the section into mechanical layers. FaultProp is used to predict the sequence of fault nucleation and propagation through this section and thus to predict likely fault density, distribution and vertical connectivity. This modelling work has application in fracture and fault development in conventional and unconventional reservoirs.
Session Ten: Development, Fractures and Geomechanics

Chairs: Richard Fox & Paul MacKay
Combining Laboratory and Computational Experiments to Increase Rock Physics Knowledge

Nicola Tisato, Claudio Madonna, Beatriz Quintal, Marcel Frehner, Maria Kuteynikova, Erik H. Saenger, Geological Institute, ETH Zurich, Switzerland

A good understanding of the effect of rock and pore fluid properties on seismic waves is necessary for the characterization of a subsurface hydrocarbon reservoir from a seismic data set. Information about the rock and fluids in the reservoir can be obtained, for example, through well logging and laboratory tests with samples cored from the wellbore. Together with seismic data, this information can be extrapolated for the dimensions of the reservoir to provide valuable quantitative estimates for production. Additionally, this information can be extrapolated in time for monitoring the spatial redistribution of fluids during production. Making such space and time extrapolations more accurate using seismic data is the main goal of rock physics. For that, identifying and understanding the physical processes taking place in a reservoir rock at different scales is a key step and the subject of our research.

We (Quintal et al., 2011a) show that combining laboratory and numerical experiments is a powerful tool to achieve an unbiased comprehension of the rock physical processes at different scales. While in laboratory experiments it is very difficult, or even impossible, to control all the physical processes, in numerical experiments all physical parameters can be controlled exactly. Numerically, it is even possible to study different physical processes separately from each other, which otherwise coexist in nature or in the laboratory.

A knowledge-feedback between laboratory and numerical rock physics is demonstrated on two examples of current challenges in rock physics: (i) understanding the influence of the rock microstructure on effective elastic properties (Madonna et al., 2012; Figure 1) and (ii) identifying the dominant physical mechanism responsible for intrinsic attenuation in saturated rocks at seismic frequencies (Quintal et al., 2011b; Figures 2 and 3).

Figure 1. Laboratory and numerical results for the P-wave velocity as a function of confining pressure, \( P_c \). The digital rock models are generated by standard segmentation (star) and watershed segmentation (triangles) of micro-CT data. The identified grain contacts have a P-wave modulus ranging from 0% to 100% of the P-wave modulus of quartz (upper abscissa). The two insets show the two end-member digital rock models containing grain contacts with a P-wave modulus equal to zero and \( M_{\text{quartz}} \), respectively. The cube volume is 2 cm\(^3\).
Figure 2. CAD-model of the Broad Band Attenuation Vessel, BBAV (Tisato and Madonna, 2012). The applied strain sensor measures the bulk attenuation and not a local attenuation.

Figure 3. Laboratory results for frequency-dependent attenuation (1/Q) for a Berea sandstone sample saturated with 60% water and 40% air, measured with the BBAV (Figure 2). Two saturation methods were applied in the laboratory: imbibitions and drainage. The significant differences in attenuation are interpreted as an effect of the different saturation distribution in the rock resulting from the two different saturation methods. Numerical attenuation simulations aiming at a better understanding of these experiments will be presented.

Both presented challenges are subject to ongoing research conducted in The Rock Physics Network at ETH Zurich (ROCKETH; www.rockphysics.ethz.ch) and the presented studies are a snapshot of work in progress. Therefore, this presentation also aims at giving an overview of our rock physics research group.
Structural Geology and Well Planning in the Clair Field

Steven Ogilvie, David Barr, BP Exploration Operating Company Ltd

The Clair Field is a giant oilfield located ~ 70 km west of the Shetland Isles, U.K. It was discovered in 1977 and brought onstream some 28 years later, in 2005. The second phase of development will consist of over 30 production and injection wells to be drilled from a second platform. Several wells are planned to be drilled from a mobile rig prior to platform jacket installation, through a seabed template. Key to unlocking the economic potential of the Clair field were a series of appraisal wells drilled in the early 1990’s that identified fractures as the primary production mechanism. Fault and fracture identification and prediction of their conductivity and connectivity therefore all play an important role during development well planning.

Structural geology contributed in several ways to the detailed planning of these wells. In the sandy tophole (Tertiary) section, outcrop analogues and offset wells were used to establish an appropriate standoff from major faults. This was to mitigate the risk of wellbore instability and fault reactivation in what is otherwise a benign sequence to drill. The intermediate upper Cretaceous mudstone section is prone to wellbore instability, believed to be caused by strength anisotropy with respect to bedding. Polygonal faulting is present and may contribute directly to wellbore stability. The associated bed rotation also influences anisotropic failure, which depends in part on the wellbore-to-bedding intersection angle, which is recorded using LWD image logs. Core acquired in the Upper Cretaceous appears to have sampled both a polygonal fault and a basal detachment. In the Devonian sandstone reservoir section, wells were placed to (i) intersect potentially productive (open) fractures and (ii) avoid potentially sealing faults. This employed a combination of seismic volumes and attributes for faults/fractures and matrix, appraisal well data including core, image logs and production logs, and the Clair Phase 1 analogue. More novel approaches for the prediction of open fractures in Clair Field are currently being tested. These include the use of a finite element model for the prediction of stresses in the overburden and reservoir.
Keynote Speaker: Comprehensive Analysis and Visualisation of Structures in Orientated Drill Core: A Minerals Perspective

Tom Blenkinsop, Economic Geology Research Unit, School of Earth and Environmental Science, James Cook University, Townsville, QLD4811, Australia

Detailed structural information obtained from drill core is essential in mineral exploration for understanding structural controls on ore geometry, and in some cases to distinguish the genetic type of ore deposit. The formal definition of resources and reserves also depends on structural analysis of drill core. A drilling program for a large mineral resource might recover tens of kilometres of 48 or 68 mm drill core; most holes will be inclined and completely cored, and in most cases the core will be orientated. Although the cost is high (a few hundred $/m in favourable circumstances), structural data from drill core cannot be supplanted because borehole imagery is not available.

Structural core logging therefore needs to be optimized to extract a range of information, and to obtain the best value from drilling. The most thorough possible structural analysis is required early in the drilling program, because sampling and weathering can make this progressively more difficult at later stages. Standard drill logging emphasises measurement of planar structures, and sometimes overlooks a wealth of additional data. This contribution describes an integrated and comprehensive system for structural core logging, and introduces some new visualization techniques. The orientation of planar and linear structures can be measured most efficiently in orientated core using a core protractor. Methods are devised to handle all types of fabric, fractures, faults and slickenlines, shear zones and shear directions, vorticity vectors, shear senses, fold hinges and hinge surfaces.

The core protractor measures orientations of structures in a reference frame relative to the drillhole and the bottom of the core, which is located by orientating the core during drilling. This reference frame is then rotated into geographic coordinates using survey data for the drillhole.

Planar structures are most efficiently measured using the $\alpha-\beta$ method, where $\alpha$ is the angle between the planar surface and the core axis, and $\beta$ is the angle measured from the Bottom of Core Mark (B) to the ellipse formed by the intersection of the planar feature and the core (Fig. 1). Lineations within a planar structure are commonly measured using a regular protractor by the $\gamma$ angle from the ellipse long axis of the plane to the lineation, but an alternative advocated here is to use a $\beta$ angle for the lineation, which has the advantage that it can be swiftly measured with the core protractor. Fold hinges can be measured from a combination of two $\beta$ angles and one distance.

One of the advantages of structural analysis from core is the three-dimensional view afforded by core. This is invaluable for vorticity analysis. A new method proposed here allows the vorticity vector to be located from a single $\beta$ measurement (Fig. 2).
Incomplete initial core logging, or new ideas that require testing, may necessitate re-inspection of core. Where samples have been taken for assays, critical intervals may be available only as half or quarter core, or not at all. All the above types of structural data can be collected in half core, with modifications to the procedures for full core to ensure accuracy (Blenkinsop and Doyle 2010).

Large amounts of data can be acquired rapidly with a core protractor, but their significance may not be appreciated at the time of measurement because the drillhole reference frame is used. It is useful, if not essential, to employ a devise such as a “rocket launcher”, which puts the core in a geographic reference frame, at the same time as measuring with the core protractor, in order to gain an immediate understanding of true structural orientations.

It is interesting to reflect on the differences between drilling and core handling techniques between the minerals and hydrocarbon industries. The emphasis on detailed structural analysis from core in the former could be transplanted to the latter, while the sophisticated application of borehole logging and imaging techniques in the hydrocarbon world might have some interesting implications for the minerals industry.

Introducing comprehensive core analysis as described above faces two challenges: the sometimes limited confidence of core loggers in structural geology, and inflexibility of existing core logging systems. Both can be met by relatively short training courses. Communication of structural results from cores in the minerals or hydrocarbon industries is another challenge. Visualisation tools that can assist include 3D rotatable images created from photographs of core, or images developed in 3D graphics software. The context of a drilling project can be well visualised in virtual globes, which are also an effective medium for illustrating surface structures.
Session Eleven: Development, Fractures and Geomechanics

Chairs: Caroline Gill & Woody Wilson
Keynote Speaker: A Geomechanical Study of the Gorm Field, Danish Central Graben: Predicting Fracture Density, Orientation and Hydraulic Behaviour in a Chalk Reservoir

Dave Quinn\textsuperscript{1}, Michael Arnhild\textsuperscript{2}, Bastiaan Jaarsma\textsuperscript{3}, Brett Freeman\textsuperscript{1}

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The Maersk Oil-operated Gorm Field began production from fractured Danian and Maastrichtian Chalk in 1981. Porosity ranges from 15 – 45\%, with matrix permeability from 0.5 – 8 mD. Faults and fractures contribute significantly to enhance effective permeability. With \(\sim\) 1000 MMstb STOIIP current production of 16,000 stb/d, infill well accuracy and optimising well interventions are important for continued development of the field.

We have employed a 3-phase strategy involving structural analysis, elastostatic modelling and static stress analysis in order to predict the density, orientation and hydraulic signature of sub-seismic fractures. The primary aim of phase one was to deliver a structurally robust framework model. This involves validation of the structural interpretation using displacement analysis of fault/horizon intersections from multiple horizons (TrapTester software).

The second phase ran forward models of mechanical response to fault slip, underlying salt movement and regional strain using elastic dislocation modelling software (FaultED). This analysis predicts the stress/strain perturbations around the set of mapped faults. At each calculation point in the reservoir, a wide range of mechanical attributes are calculated, including fracture mode and orientation, and proxies for fracture intensity. The application of FaultED to the effects of salt movement is a new technology relevant to most reservoirs where salt is in play. Image log data from 13 wells provide a first order, independent assessment of the predictive method. Comparison between the predicted and observed fault/fracture orientations and densities in the wells yields encouraging correlations. Ultimately these fracture model results are used to condition permeabilities in the fluid flow simulations.

The third phase of the project used the StressTester software to resolve in-situ stresses onto the predicted (and image log) fractures. This analysis estimates the proximity to failure hence likely hydraulic conductivity/resistivity. We find a positive correlation between observed hydraulic signatures in the image logs and our geomechanical predictions.

Following this study a well was successfully drilled in an area of predicted high fracture density that had “much higher productivity than predicted by matrix properties modelling” (Arnhild \textit{pers comm.}).
Testing Restoration-Based Fractures Prediction within a Fault Damage-Zone in Carbonate Rocks: The Filettino Fault, Central Apennines, Italy

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The prediction of fracture distribution in the subsurface is currently one of the most important and difficult challenges in applied structural geology studies, from the resource extraction sector, to sequestration or engineering. Fractures are known to correlate with both fold and fault-related deformation over time (Aydin, 2000; Tavani et al., 2008; Agosta et al., 2009). Damage-zones related to fault activity are made up by a network of subsidiary structures (i.e. joints, stylolites and shear fractures). These zones bound the fault-core and generally enhance the permeability of a fault zone (Caine at al., 1996; Wibberley et al., 2008; Agosta et al., 2010; Faulkner et al., 2010). Therefore, the quantitative characterization of the architectures of a damage-zone, in terms of fracture orientation and distribution, is fundamental to predict the pathways of geo-fluids faulted regimes.

With this work we aim to test the validity of restoration-based predicted fracture patterns in carbonate fault-damage zones by means of a direct comparison with outcrop-based data.

The studied fault (Filettino Fault - N 41°53'08” - E 13°18'37”) is a regional scale normal fault located in the Central Apennines (Italy), which crosscuts the Meso-Cenozoic units of the Latium-Abruzzi carbonate platform (Fig.1 – a). The fault strikes N104E and dips 35°SW, it is located on the crest of a thrust-related fold oriented NW-SE (Fig.1 – b). The Filettino Fault juxtaposes Triassic dolostones in the footwall and Lower Cretaceous carbonates in the fault hangingwall (Mannino, 2012).

Two discrete fracture network (DFN) models were built. The first one is a deterministic model populated by data derived from scan-lines (Fig.1 - c) and associated field data from the Filettino fault. The second model was obtained by constructing a 3D model of the Filettino fault and restoring the present day fault off-set in order to capture the strain distribution at different stages of deformation. The DFN was then populated using the (forward modeled) computed strain maps as proxies for both the intensity and orientation of fractures.

The comparison between the two models shows a reasonable match between the outcrop fracture data and the predicted fracture pattern using restoration-based proxies. We conclude that the restoration-based fracture prediction provides an efficient tool for predicting fracture patterns within fault damage-zones.

Acknowledgements

Both 3D model building and restoration were performed using the commercial software package MOVE provided by Midland Valley Exploration Ltd.
Fig. 1 – a - Geological maps of the studied area (modified after “Carta Geologica d’Italia 1:50000) and data location; b – Lower hemisphere equal area projection of the bedding and fault; c - Fault-related fractures scan-lines.
Unlocking Resources in Fractured Reservoirs Using Geomechanical Tools – An Example from the Hoton Field, Southern North Sea

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Originally developed as a conventional reservoir, the Hoton field in the Southern North Sea gas basin has shown to deliver economic rates from a tight and fractured Permian Lower Leman Sandstone Formation. Hoton is divided into a northern and southern area by a complex, steeply-dipping ESE-WNW trending fault zone. The northern part of the field is developed via a tri-lateral producer, but the field’s southern half, which appraisal drilling showed to consist of even lower matrix permeability than the northern part, was deemed to be too tight for a conventional development.

Roughly one third of the fields resource of dry gas lies within the southern part of the field. A re-assessment of the southern area’s development potential using geomechanical tools strongly suggested that it also could deliver commercial well rates, similar to those experienced in the northern area of the field. For the northern area, observed well productivity was interpreted to be due to a strong contribution from fractures. If a similar fracture contribution could be expected in the south, additional development wells could be considered to access the resource in the south. Unlocking the southern resource thus required an assessment of the potential fracture network productivity in that area. This necessitated a subsurface description that integrates an understanding of the structural history with a quantitative assessment of the driving mechanism that creates the fracture permeability.

We summarize the structural history of Hoton into two major tectonic phases that affected the area, namely Mesozoic E-W extension followed by N-S Tertiary compression and uplift. We assume that both phases have propagated separate fault geometries, such that early, mainly extensional faults were cross cut by shallower-dipping compressional faults. We interpret the compressional and uplift phase as having reactivated earlier-formed fractures. Shear reactivation in conjunction with uplift is interpreted to have re-opened fractures that now provide permeability assist to the tight matrix.

Structural reconstructions using Dynel2D/3D and forward modelling using Poly3D of the two tectonic phases helped to establish not only the relative contributions of the two tectonic events to the observed deformation at top reservoir, but they also constrained the likely geometries of the faults involved in the two tectonic phases. Using the different fault geometries, forward stress analysis using Poly3D showed that most of the observed fractures along wells might have developed during the late Mesozoic E-W extension. The analyses also showed that shear stresses resulting from the Tertiary compression in both areas of the field were likely to be of similar magnitude, and therefore the potential to reactivate earlier formed fractures was also similar across the field. The computed shear stresses of the later tectonic event, which we use a proxy for reactivation, was then used to drive discrete fracture network (DFN) models. Production profiles and estimates of ultimate recovery, calibrated to the northern area of the field, were generated in a reservoir simulator after combining the DFN models with a description of the matrix.
Keynote Presentation: Applied Structural Geology in Petroleum Exploration and Production

Steve Jolley, Shell Canada Limited, Calgary

Applied Structural Geology can be considered in terms of its role in the science of petroleum systems; and how it adds value to exploration and production. This paper reviews the value-add of structural geology to subsurface projects; the practical challenges of applying structural geology within integrated subsurface workflows; and the feed-back loop between project work and the science and technologies we apply.

Folds, faults and fractures exert a major control on petroleum trapping and production. Given the potential for structural features to either enhance or severely reduce the value of petroleum reservoirs, and for their hydraulic and geo-mechanical properties to change under field production, there are massive value and HSE implications. In order to make appropriate exploration and field development decisions, we must distinguish between ‘good’ and ‘bad’ structural assemblages. This requires proficient basic interpretation, mapping and modelling; the integration of modern analyses and modelling tasks within our subsurface workflows; and the translation and inclusion of study results. However, it is an industry wide experience that the structural aspects of the workflow are sometimes under-applied. This can lead to exploration failures and field development surprises, that tie back to ‘missed’ structural controls.

Most asset-based geoscientists are familiar with the more obvious basic tasks, such as fault mapping. The ability to perform these tasks well, is linked to skills and training, data quality, appropriate tools, and project time pressures. However, there are a number of ‘industry standard’ structural workflows that thread into generalist integrated workflows – with various sub-tasks needing to take place in different discipline areas of the generalist workflow. Team awareness and effort is required to ensure that the structural geology concerned is used and applied correctly. Consequently, many structural geology practitioners are concerned with the task of distilling complex structural geology into forms that can be applied within integrated workflows against tight project timelines.

Since the structural aspects of a subsurface workflow span different disciplines, this gives scope to cross-check results, test predictions and sensitivities, update interpretations and model parameters - to achieve static-dynamic consistency with the data. Some companies call this activity ‘closing-the-loop’. It leads to improved subsurface assessments and field development choices – and it has enabled new, valuable information to feed-back into scientific research.
Poster Presentations

Abstracts

(Alphabetical order)
Fractures can influence fluid flow in sandstone hydrocarbon reservoirs. Understanding the geometrical attributes of individual fractures and their patterns is a critical step in quantifying their connectivity. The quantification of fracture attributes and fracture patterns from outcrop analogues can aid the construct of testable expressions for 2D and 3D scaling relationships. These relationships can be used in fracture prediction in subsurface reservoirs.

Data from cataclastic deformation bands have been collected from selected outcrops with a variety of sub-horizontal and sub-vertical rock faces. Deformation bands and their patterns have been mapped in outcrops of aeolian sandstones of the Entrada formation in SE Utah (USA) and the Hopeman formation in Moray (Scotland).

We have quantified the geometrical attributes of lozenges and lenses in faulted sandstone. We use the term lozenge to refer to the area or volume of relatively undeformed rock situated between two strands of a composite deformation band, and a lens is an approximately rhombus-shaped rock body bounded by slip surfaces. We took 8 samples from each locality, approximately 25 by 20 by 15 cm in size. Each sample was cut into 12-15 slices approximately 0.8 cm thick to measure the geometrical properties of the deformation band network (Figure 1). The dimensions of ten lozenges have been measured from each slice. The shapes of the lozenges between deformation bands are anisotropic i.e. lozenges have a long axis parallel to the strike of deformation bands (X axis), an intermediate axis parallel to the dip direction of the bands (Y axis) and a short axis normal to the plane of deformation band (Z axis). The dimensions of the lozenges (X, Y, Z) have been measured and are presented in Flinn diagrams (Flinn 1962). Based on these data, the lozenges have oblate shapes. In addition, we have investigated the statistical trends among different lozenge and lens datasets (Goblin Valley, Hopeman, Bartlett Wash) and explored their potential correlation to other attributes of the fracture pattern and the petrophysical properties.

**Figure 1:** (a) Photograph of samples cut into slabs and (b) a schematic diagram of a lozenge showing the reference frame in 3D.
Figure 2: Flinn diagrams of shapes of the lozenges in Hopeman (Scotland) and Goblin Valley (USA). Note that the lozenges have pancake (oblate) shapes (i.e. X≥Y>>Z).

We used Positron Emission Tomography to analyze the fluid distribution and monitor the flow through sandstone samples containing deformation bands. Two samples (2.5 by 3.5 by 4 cm) were prepared and setup in different orientation (XZ and YZ). The samples were completely sealed from sides and bottom with polycarbonate sheets and silicon. PET acquisition of 24 hours was run with time frames of one hour for each sample. The activity concentrations were 13 MBq in 10.4 ml and 17.6 MBq in 14 ml of water for samples 1 and 2, respectively. The obtained images demonstrate that fluid flow along strike direction is relatively faster compared to the flow along dip direction of deformation band strands (Figure 3). We are exploring the relationship between connectivity of lozenges and fluid flow.

Figure 3: a) Sandstone sample containing deformation bands in preparation for PET acquisition. b) PET images show fluid flow through time (1 hour frame) for the same sample.
A Reappraisal of the Deformation History, Kinematics and Absolute Age of Faulting in the West Orkney – Orcadian Basin System, Caithness, Scotland

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The faults and Devonian sedimentary rocks of the Orcadian Basin, Northern Scotland have long been used as a surface analogue for the fractured Devonian and Carboniferous strata that form the Clair Group, the main sub-surface reservoir sequence of the Clair oil field located west of Shetland. Most published accounts have assumed Devonian ages for the mainly extensional faulting in the Orcadian Basin, with some limited inversion and reactivation proposed during the Carboniferous. More recently, however, regional studies, palaeomagnetic dating of fracture fills and structural studies in the adjacent basement rocks suggest that significant amounts of faulting may be related to the development of the contiguous offshore West Orkney Basin during the Mesozoic. Here we present a new study of the structures cutting the Devonian rocks and their immediate basement in the northern coastal region of Caithness.

Figure 1: Locality map

The purposes are: i) to establish whether there is evidence for multiple ages of faulting in this region, ii) to reassess the nature and significance of the locally developed so-called inversion structures; iii) to use Re-Os geochronology to assess the absolute ages of fracture fills and faulting; and iv) to consider the implications of these findings for our current understanding of fracture systems in the Clair Group offshore.

Though field and microstructural analysis two distinct groups of faults and associated structures are recognized, each with different and distinctive fault rocks and fracture fills:

‘Group 1’ faults (Fig 2a) trend N-S, NW-SE and WNW-ESE and display predominantly sinistral strike slip to dip-slip extensional movements. Gouges and breccias associated with these faults consistently display little or no mineralization or veining (Fig 2b). These faults form the dominant structures in the eastern part of the northern coastal section in Caithness. Group 1 structures are locally reactivated synchronous during Group 2-age faulting (see below) - especially in the western coastal sections where they may display significant strike-slip movements.

‘Group 2’ faults (Fig 3a) trend mainly NNE-SSW, NE-SW and E-W and display predominantly dextral to extensional displacements. Characteristically they are associated with widespread syn-deformational carbonate mineralisation (+/- pyrite and bitumen) both along faults and in mineral veins (Fig 3b). These faults are dominant in the western parts of the coastal section and become less widespread east of Dunnet Head. Folding (mm to m scale) –previously attributed to regional inversion - is almost always associated with (Group 2 age) fault zones.
that have a strike-slip component of movement. Preliminary Re-Os dating of both pyrite and bitumen suggest early Mesozoic ages for Group 2 structures.

Figure 2) Group 1 structures

Figure 3) Group 2 Structures and mineralisation

On the basis of these initial observations, we suggest that:

i) At least two distinct phases of rift-related faulting are recognised in the West Orkney-Orcadian basin system:
   - An older Devonian episode of ENE-WSW extension (Group 1 faulting) related to regional sinistral transtension along the Great Glen Fault and;
   - A younger early Mesozoic episode of NW-SE extension (Group 2 faulting) that partially reactivated earlier structures

ii) Previously interpreted inversion structures are of local significance and may be related to local strike-slip movements along specific fault structures formed or reactivated during Mesozoic rifting.
This research describes anisotropic and heterogeneous microstructures within faulted high porosity sandstones, and explores the influence of these variations on the hydraulic and mechanical properties of the rock. By integrating quantitative field, laboratory and digital image data we can begin to understand and predict the behaviour of fluids during and after faulting and infer the impact of petrophysical patterns on rock mechanics. Previous research has shown that changes in pore fluid pressure, associated with fluid flow, can induce changes in the stresses acting on the rock (Teufel et al., 1991). Theoretical work suggests that, depending on the orientation of anisotropic pores and cracks with respect to the principal stresses, anisotropy of porosity may either increase or decrease the stability of the faulted rock (Chen & Nur, 1992; Healy, 2009).

Porous sandstones sampled from a surface outcrop of an extensional fault zone show anisotropy of petrophysical properties in three orientations; (x; perpendicular to the fault plane, y; down the dip of the fault plane and z; parallel to the fault plane). This anisotropy is independent of any precursor sedimentary fabric permeability and only related to microfracture type and distribution and variations in pore geometry (Figure 1). Permeability data collected using ambient pressure permeametry and a confining pressure permeameter from over seventy oriented core plugs show higher permeabilities ($k_{max}$) down dip to the fault plane (y) relative to along fault strike (z). The permeability of cores drilled perpendicular to the fault plane is variable and can be $k_{max}$ or $k_{min}$ depending on the specific fault architectural unit sampled, and the location along fault strike. Permeability anisotropy is up to 3 orders of magnitude in some sample sets and remains consistent at confining pressures between 10 MPa and 100 MPa (equivalent to ~4 km depth), and will therefore be significant in the subsurface.

Porosities measured using a helium porosimeter are comparatively isotropic in three orientations. Digital image analysis from over forty thin sections sampled from the ends of core plugs (Figure 1) show variations in 2D porosity of up to 10 percent between orthogonally oriented sections. Porosity anisotropy tends to show higher percentage porosities down dip to the fault plane (y) close to the fault slip surface (<10 cm) equivalent to $k_{max}$, while samples from >10 cm from the fault tend to show higher porosities along strike (z), in contrast to the $k_{max}$ orientation.

Further investigations using cathodoluminescence (SEM-CL) and back scatter electron microscope (BSEM) images have enabled identification of microfracture types and strike orientations in three orthogonal sections (Figure 2). Distributions of microfractures indicate that common alignments may be preferentially connecting pore spaces creating anisotropic flow pathways close to the fault slip surface. Pore geometries have also been quantified using pore size, shape and orientation of pore long axis and show dominant pore axis alignments down
dip to the fault relative to a broad dispersion of pore axis orientations in sections perpendicular to the fault plane.

Tectonic pore deformation includes formation of elongate pores through grain reorganisation, grain boundary dissolution and secondary porosity formed along fluid flow pathways. The potential impact of these tectonic porosity patterns on permeability during faulting can be inferred through preferential quartz cementation of pores and cemented microfractures using cold cathode CL and SEM-CL.

In this study, an integrated, quantitative analysis of fracture and petrophysical datasets collected across a range of scales around a normal fault zone has shown structural heterogeneity connected to petrophysical anisotropy in a clastic reservoir analogue. This anisotropy potentially impacts on across-, up- and along-fault fluid flow, and may also influence the mechanical stability of the fault zone.

Figure 2 Microfractures in quartz and feldspar grains
Dynamical unfolding is a recently developed method to reconstruct folded geological cross-sections (Schmalholz, 2008; Lechmann et al., 2010; Frehner et al., 2012). Thereby, the present-day fold geometry is discretized in a finite-element model (Figure 2a) and subsequently extended by applying horizontal extensional boundary condition in the numerical simulation. This corresponds to a time-reverse simulation and various stages in the fold development can be investigated. Compared to classical palinspastic reconstruction techniques, dynamical unfolding allows incorporating rheological parameters and therefore studying the influence of rheology on the fold development. For example, Frehner et al. (2012) could identify interfacial slip between lithological units as a key deformation process during the development of the Zagros Simply Folded Belt in the Kurdistan region of Iraq (Figure 1).

Besides estimating bulk shortening values, dynamical unfolding is also able to identify problematic areas in the geological cross-section (Figure 2b). These areas, where the dynamical unfolding is less efficient, may be characterized by either

1. higher geological complexity or
2. inaccurate cross-section construction.

The first point includes various deformation processes, such as intense brittle fracturing and faulting, non-volume conserving processes (e.g., solution-precipitation, compaction), or three-dimensional out-of-plane deformation. These processes are (currently) not included in the numerical algorithm. However, dynamic unfolding can identify these areas in the geological cross-section and therefore helps define targets of future field investigations.

The second point can be due to sparse or inaccurate data, from which the cross-section is constructed, or due to the cross-section construction method itself. Dynamical unfolding can identify areas in the cross-section, which are not well constrained or badly constructed. Therefore, dynamical unfolding is a valuable tool for quality control of geological cross-sections.

The presented work demonstrates how dynamical unfolding can be applied for both quality control and planning field investigations. As a case study the Zagros Simply Folded Belt in the Kurdistan region of Iraq is used.
Figure 2: a) Present-day geological cross-section of a part of the Zagros Simply Folded Belt discretized with a finite-element mesh. b) The same cross-section after dynamical unfolding applying 12.4% extension in a finite-element simulation (corresponds to 11% shortening in a forward-time experiment). The mean fold amplitude decrease from a) to b) is 65.3%. The colorbar schematically indicates areas along the cross-section with efficient amplitude decrease (green) and less efficient amplitude decrease (red). This simulation corresponds to the gray dashed line in Figure 1. Modified from Frehner et al. (2012).

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Spatial Characterisation of Fracture Systems: A Comprehensive Global Database of Fully-Attributed Multi-Scale Fracture Data


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

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

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

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A study of borehole image data acquired from eight wells drilled as open hole completions into highly fractured basement has identified open and stress-sensitive fracture sets. This information together with seismic interpretations of fault damage zones, production and gas log data has helped to constrain basement targets in the Bayoot Field, Block 53, Yemen. However the dominant productive zones within the basement appear to be within seismically resolvable fault damage zones that should in theory be closed under the present-day stress regime. Sidewall core examination has shown evidence for cement bridging between fracture surfaces and this propping effect is envisaged along these major faults. A dual porosity system is hypothesised whereby open critically stressed fractures act as hydrocarbon conduits into the seismic-scale faults.
Analogue Models of Lithospherical-Necking Evolution during Rifting

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We use analogue models to study the evolution of necking during orthogonal rifting at lithospherical scale. By mean laser-scanner device we detect model’s topography evolution, i.e. basins and faults formation and development, as well the lower boundary of lithospherical ductile mantle. In our models we simulate a typical “cold and young” 4-layers lithosphere stratigraphy: two layer in the crust - brittle upper crust (BC) over ductile lower crust (DC) - and two layer in the lithosperical mantle - brittle upper mantle (BM) and ductile lower mantle (DM) - that rest on the asthenosphere.

By monitoring the evolution of model all over the deformation and final depth of each layer we are able to depict the evolution of thinning factor for both the whole lithosphere ($\beta_z$) and the crust ($\gamma$). The area of effective stretching ($\beta_y$), parallel to the extensional direction, is defined in map view using the evolution of $\beta_z$. Using a backstripping analysis implemented in the MOVE software we attempt to define the value of models thinning- and stretching-factors throughout his deformation history.

The presented technique coupled analog models and analysis of surface evolution using software of structural analysis (MOVE - Midland Valley). This methodology allow an effective determination of thinning factor along the extended lithosphere, which in turn let a better constrain of the thermal regime of the extensional area.
Investigating the controls on Chalk structuration in the Central North Sea

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The genesis of post-rift (Cretaceous and Tertiary) structures in the Central North Sea has variably been attributed to effects of halokinesis and compressional reactivation of normal faults (tectonic inversion). Interpretation of high fidelity 3D seismic data in UKCS Quadrants 29 and 30, constrained by 40 wells, the structure was found to be a result of salt diapirism through the footwall of the Jurassic normal fault folding the units above it, rather than the reactivation of the precursor faults.

An anticlinal ridge was identified at the level of Base Cretaceous Unconformity, above which are folded Cretaceous chalks and mudstones, in block 29/10 of the North Sea. Local formations containing key hydrocarbon reservoirs are generally considered to only have been deformed by post-rift thermal subsidence.

Basement faults mapped at Top Rotliegend show that a series of E-W trending Permian normal faults are cross-cut by three large NW-SE trending Jurassic faults creating the basement structure in the area. Flow of Zechstein evaporites originated from the top of the basement fault blocks and flowed into the Jurassic footwalls to form diapirs and effect the prospective Triassic and Jurassic reservoir sandstones.

The anticlinal ridge created by the diapirism has an east-west strike and it is approximately 20km long and 10km across. It is formed by the reactivation of a fault block, bound to the south and east by normal faults, dip closure to the north and abuts the Mid North Sea High to the west. At the eastern end of the ridge, a dome forms above a salt diapir within the underlying Jurassic sandstones. By flattening seismic sections on key horizons within the Cretaceous chalks, it is evident that the main period of diapirism occurred post-dates Lower Cretaceous Cromer Knoll Group deposition but was initiated in and synchronous with deposition of the Hod Formation (100-70Ma). Diapirism finally stopped during the Early Tertiary during the deposition of the Hordaland Formation.

Salt withdrawal from the depocentre to the east of the anticlinal ridge, to form the aforementioned diapir, led to the formation of a turtle-back anticline structure centred on the depocentre of the Cromer Knoll Group. As the salt flowed out during latter stages of the Cretaceous, the edges of the basin subsided creating an anticlinal structure in the sediments within the basin. The salt formed two further diapirs surrounding the basin, one to the north-east and one to the south.
Modeling Near Surface with Shallow Borehole Information

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The characterization of the near-surface layers becomes nowadays extremely important for a clear interpretation of seismic data. The development of a detailed model of the weathered zone, and in particular a structural model with the subsurface geometries and a velocity model, allows correcting most of the problems deriving from peculiar situations. The combination of borehole and field data in a three-dimensional framework will improve the interpretation of already existing seismic data and add valuable information for numerical studies.

As a test study, we developed an integrated 3-D model of the shallow surface geology and of the shallow velocity field of an area of 187 km² above an underground gas storage site in the south-western part of the Paris Basin. The geology of the site is well studied and characterized at the gas reservoir level, but there are not publicly available models for the near surface geology. A few outcrops allow the observation of a shallow stratigraphic column consisting of sedimentary rocks spanning from Late Cretaceous to Pliocene. The Cretaceous sediments consist in terrigenous chalks and their weathering products, while the formations deposited during the Cenozoic are mainly continental, with the exception of one late marine episode. The youngest deposits are fluvial terraces that cover most of the area east of the facility.

The raw data used to generate the model interfaces are stratigraphic markers, lithological columns and uphole surveys derived from 512 boreholes belonging to the public repository of the Geological Survey of France (www.brgm.fr/infoterre). Topographic and geological maps and digital elevation model were additionally used to improve the reconstruction of the lithological interfaces in the model, knowing the formation limits at the topographic surface.

The generation of the structural model comprised some major challenges, mainly because the borehole data represent 1D vertical pinpoints into the subsurface, rather than 2D sections as it is the case for most seismic surveys. This complicated the cross-correlation between the boreholes and the interpolation of the lithological formations in the 3D space.

Horizons were modeled with Petrel interpolating the stratigraphic well markers. 2-D grids were generated, each representing the top surface of a specific formation, and then were subsequently used as a guide for structural interpretation. We looked for evidences of faults and strong marker displacements in the boreholes and then compared our observation with measurements of local and regional trends in the Paris Basin and with cross-sectional views of the horizons. The detection of structural anomalies, in particular localized dip and thickness variations was enhanced using edge detection and isopach maps. The obtained horizons and faults were used to define the 3D geocellular model, in which facies and velocity logs were then upscaled and distributed based on a geostatistical analysis.

The 3D geological model clearly shows the presence of an anticline in the Cretaceous sediments with a NW-SE direction (Fig.1.a). The analysis of boreholes, maps and cross-sections suggests that this anticline is dissected by preferably meridian-trending structures. The fault surfaces obtained are in agreement with the deep Triassic fault system highlighted by two depth maps as shown in Fleury et al., 1997. These faults seem to affect not only the Cretaceous but also the uppermost formations, being reactivated during Cenozoic. Most of the faults are concentrated in the facility area and have conjugate directions N10E-N30W; some of them are aligned N70E-N80E-N120E. They have short displacements that decrease upward, except for two points where it was possible to identify two faults isolating a “cone” of chalk. Such displacement features could also be accentuated by dissolution processes and alteration of the chalk driven by pre-existing fractures.
The 3-D Vp model reconstructed from the velocity well data shows a constant increase of the velocity in depth with localized velocity inversions (Fig. 1.b). To better constrain the velocity model, laboratory measurements of P-wave velocity were conducted on core plugs taken from 24 hand specimens. The measurements were conducted employing the pulse transmission method for compression (Vp) and shear (Vs) waves in dry and fully water saturated conditions. These measurements improved the understanding of the borehole velocity model explaining the anomalies observed. Such anomalies in fact can be caused by lateral heterogeneities in the characteristic facies of a specific formation, as in the case of silicified Cenozoic levels, or by porosity variations related to strong diagenesis in the Cretaceous chalks.

Further developments include using the 3D model as a starting point for numerical simulations of near-surface effects in seismic data, improving the comprehension of ambient seismic wave field attributes.

Fig.1 W-E cross sections through the 3D model showing the main lithologies (a), p-wave velocity from uphole survey data (b), p-wave velocity from laboratory measurements (c), experimental s-wave velocity derived from the application of a wet Vp/Vs ratio(d) to the Vp borehole model.
Alpine fold and thrust structures: a 3-D model of the Säntis area (Switzerland)

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The Säntis area offers one of the most spectacular insights into the fold-and-thrust belt of the Helvetic nappes. The nearly perfect outcrop conditions, combined with the exemplary intersection of formation boundaries with topography, make it a natural laboratory for structural geology. Since the pioneering work of Heim (1905) at the beginning of 20th century, the area was mapped in detail (Eugster et al., 1982) and investigated in terms of deformation mechanisms (e.g. Groshong et al., 1984), structural evolution and fold-thrust interaction (Funk et al. 2000; Pfiffner 1982, 1993 & 2011). The proposed restorations are mostly 2 dimensional palinspastic reconstructions, either in map or in cross sectional view.

The main goal of this research is to better understand the geometrical relationships between folding and thrust faulting, investigating for example fault-propagation folds and analyzing the lateral changes of folds and thrust structures along strike. A three-dimensional model of the area is built using 3D MOVE, combining cross-sections from Schlatter (1941), Kempf (1966), Pfiffner (in Funk et al., 2000; 2011), the geological map 1:25.000 by Eugster et al (1982) and a digital elevation model (DEM) with a regular grid of 20X20 m.

Six main horizons are reconstructed, corresponding to the base of the Öhrli and Betlis Limestones, the Helvetic Kieselkalk, Schrattenkalk and Garschella Fm and the Seewen Limestone. The main structural elements in the Säntis area, such as the Säntis Thrust or the Sax-Schwende Fault, are also implemented in the model. The 3-D model obtained highlights the shape of the main anticline-syncline pairs (e.g. Altmann-Wildeeli, Schafberg-Moor, Roslenfirst-Mutschen, Gulmen etc...); such fold trains vary in amplitude and wavelength along strike. The model also shows clearly the lateral extension, the trends and the variations in displacements of the principal faults. The reconstruction of 3-D horizons allows the geologists to investigate cross sections along any given directions. The 3-D model is useful to understand how the changes of the internal nappe structures, namely folds and thrust faults, change along strike. Such changes occur either across transverse faults or in a more gradual manner. The model will be also used as a base to perform strain estimation and retrodeformation.

Fig. 1. Lateral view of the 3-D model, showing the present days fold-and-thrusts structures.
Distinguishing Structural Styles and Evolution of the Salt and Shale Tectonic Provinces of the Western Gulf of Mexico

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The Western Gulf of Mexico (GoM) is a passive margin basin characterised by a gravity-driven thin-skinned system. Cenozoic tectonic-structural deformation resulted in an updip extensional province of growth faulting located in the area of the coastal plain and continental shelf, and a downdip contractional province, the Mexican Ridges fold belt, of detachment and fault-related detachment folding covering the continental slope.

The northern sector of the Mexican Ridges is a frontier area where typical shale-related deformation interacts with salt tectonics to produce a structural domain of salt detachments, allochthonous salt, shale diapirism and mud volcanoes. In order to differentiate salt and shale structural styles, key criteria on seismic response and deformational mechanisms were applied during 2D and 3D interpretation; in particular, in areas of complex deformation and low seismic resolution. In addition, to reconstruct the tectonic-structural evolution, some regional cross-sections (RCSs) were constructed and restored, from north to south, across the present-day shallow salt structures, the transition between salt and shale structures, and the sector with no shallow salt.

As a result of this structural analysis we present an evolutionary model from the original Jurassic autochthonous salt basin to the present-day structure of the salt province dominated by an extensive salt canopy. Finally, considering kinematic modeling of the Northern GoM and other salt basins, we estimate salt loss and propose an autochthonous salt basin less extensive than previously interpreted. These results are relevant to characterize not only the evolution and structural styles of passive margins, but also, evaluate deformation, timing of trap formation, migration pathways and hydrocarbon potential of salt and shale structures.
Triassic to Cretaceous carbonate formations at Jebel Madar, Oman form the exposed and deformed beds overlying a salt dome. They contain a fracture network that reflects burial and exhumation in addition to the impact of regional tectonics and the local salt intrusion. By studying this fracture network it is possible to constrain the deformation history of the salt dome, and establish how the fracture network developed over time. This outcrop can also serve as an analogue for fracture networks above sub-surface intrusions in reservoir settings, bridging the gap between seismic and well-log scale. Here, fractures can act as barriers, baffles or conduits for circulating fluids. The fracture connectivity, which is a controlling factor for fluid flow in the subsurface, is critically dependent on the relative age of individual fracture set, i.e. the connectivity depends on the chronology of fracture development. Fracture orientations above salt diapirs can follow fracture trends caused by regional stress fields operating prior to the intrusion and/or represent trends that developed in response to the intruding salt. The extent to which these fractures occur becomes important when predictions are being made about the geometry and properties of subsurface plays. Tectonic and fracture studies at Jebel Madar have focused mainly on the Cretaceous Natih formation (Blake, 2009; Claringbould, 2010; Montenat et al., 2000), which is the youngest formation outcropping at the rim of the salt dome.

In this study we carried out fracture analyses at six different locations i.e. in the Rayda, Salil, Habshan, Lekhwair and Natih formations across the salt dome at Jebel Madar in order to obtain fracture orientations and define fracture sets from the whole study area. Fracture orientations were measured along outcrop faces and on the top of bedding surfaces. The relative age of fractures were deduced by examining cross-cutting and abutting relationships on bedding surfaces. Younger fractures tend to curve into and/or abut against pre-existing open fractures. The majority of fractures at Jebel Madar are perpendicular to bedding. Fracture orientation was therefore determined for when the beds were horizontal. Here, we present preliminary results comprising fracture orientation and fracture sets. We also attempt to link the sets to regional and local tectonic events. The majority of fractures are opening mode fractures, and their orientation is perpendicular to bedding. A NE-trending fracture set was identified in the majority of the locations. We interpret this set to represent a main, pre-intrusion, regional fracture set. De Keijzer et al. (2007) found a dominant fracture set at the Jebel Madmar anticline to the west of Jebel Madar and suggested that this represented a regional fracture set developed at the start of Alpine Phase II (Eocene to Pliocene) which involved a regional NE-SW compression in Northern Oman.

On-going research is being carried out including fracture spacing, petrographic and geochemical analysis of fracture cements, stylolite mapping, assessment of large-scale fractures and faults at Jebel Madar in an attempt to determine the history of salt intrusion and the detailed geometry of the associated fracture network.

This project is part of the Qatar Carbonates and Carbon Storage Research Centre, which is jointly funded by Qatar Petroleum, Shell, and the Qatar Science & Technology Park.
A Study on How Cap Rock Geometry Influences the CO₂ Storage capacity

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CO₂ can be stored in oil and gas reservoirs or in suitable aquifers. In a suitable location, the probability for leakage must be small, the storage capacity must be big enough, and injection of CO₂ through wells must be possible. An important trapping mechanism of CO₂ is structural trapping, which means accumulation under a cap rock.

We present a study on how different cap rock geometries will influence the CO₂ storage capacity. Alternative cap rock geometries are created by combining different stratigraphic with different structural scenarios. For depositional features, two scenarios were chosen for which it was considered likely that a depositional/erosional topography could be preserved under a thick regional seal; the latter commonly formed by marine shale. The two scenarios reflect situations where sand deposition is succeeded by deposition of fines as a result of marine transgression:

- Offshore sand ridges covered by thick marine shale
- Preserved beach ridges under marine shale

For comparison, we also look at a flat model.

Figure 3: Example of stratigraphic top surfaces. To the left, offshore sand ridges, (OSS), and to the right, the flooded marginal marine system (FMM).

We generate two different structural scenarios, one with all faults normal to flow direction, and one with faults both normal to flow direction and with an angle of 60 degrees with flow direction.

Figure 4: Example of simulated fault patterns with one fault direction (left) and two fault directions (right). Both stratigraphic and structural scenarios are stochastically generated, and uncertainty studies are performed. The storage capacity is calculated by a simple and fast spill point analysis, and by a more extensive method including fluid flow simulation where parameters such as pressure and injection rate are taken into account. Results from the two approaches are compared.
The study shows that cap rock geometry is of great importance to the storage capacity.
Modelling the Evolution of the Indian Ocean 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 to serve as a basis for palaeogeographic mapping. Traditional ‘rigid’ plate reconstructions create overlaps and underfit of plates when restored to their pre-rift positions, which can be attributed to a combination of poorly defined continent-ocean boundaries and internal deformation in the process of rifting and continental break-up. When plate reconstructions are used with located point (e.g. well), line (e.g. seismic) and polygon data this problem is critical.

For the Indian Ocean, plate tectonic reconstructions based on the relative motions of Africa, Madagascar, India and Antarctica during the breakup of Gondwana that do not take into account the complex effects of deformation; particularly between India and Madagascar, India and the Seychelles and India and Antarctica are a particular problem. A deformable plate model is in development that builds on the current rigid plate model. It describes the complex multiphase break-up history of Africa, Madagascar, Seychelles and India, the associated magmatic activity and the subsequent northwards drift of India through the Eocene, before its collision with Eurasia. The break-up of Gondwana was initiated in the mid Jurassic by rifting between the Antarctica--India-Madagascar-Australian plates and Africa. This was followed in the Late Jurassic by the drift of India away from Australia and the Cretaceous breakup of India and Antarctica. The opening of the Mascarene Basin in Late Cretaceous and the northwards drift of the Seychelles-India block was followed by the separation of India and the Seychelles and the eruption of the extensive Deccan flood basalts.

Crustal domains on volcanic margins can be very difficult to define due to the presence of additional magmatic material. On these margins, there is consequently much speculation as to the position of the continent-ocean boundary and the timing of rifting and sea-floor spreading. In the Western Indian Ocean the presence magnetic anomalies indicating variable rates of seafloor spreading and ‘jumps’ in the axis of seafloor spreading have not as yet been satisfactorily resolved by existing plate models.

Integration of detailed geophysical and geological datasets, combined with information from published literature will be used to produce an enhanced plate tectonic model for this region. This will be coupled with deformable modelling of the extensional margins, incorporating stretching (β) factors to calculate the extent of crustal deformation. The results of this work will mean that determining the pre-rift geometries and palaeo-positions of the plates and the spatial relationships of associated datasets will be much more accurate. This will have positive implications for future hydrocarbon exploration in the region.
Structural Reservoir Heterogeneity Induced by Forced Folding in Sandstone Reservoirs: the San Rafael Reef Monocline, Utah, USA

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Forced folds, in the form of fault-propagation monoclines, are commonly found above extensional and contractional faults. Strain associated with and localized in such folds may result in the nucleation of fractures, faults and/or deformation bands, which, if occurring in a subsurface reservoir setting, can impact fluid flow. In the present study, we investigate the well exposed forelimb of the San Rafael Reef Monocline, in which the Lower Jurassic eolian Navajo Sandstone contains numerous arrays of low-permeable deformation bands. This unit is the reservoir of several producing petroleum fields in Utah, and analogous for a wider range of eolian sandstone reservoirs worldwide (e.g. the Rotliegendes sandstone of the Southern North Sea).

The spatial distribution and characteristics of the deformation bands were analyzed based on structural and petrophysical data collected along several canyons crossing the monocline. Field observations suggest a direct relationship between forelimb dip and frequency/complexity of deformation band arrays. The shear zones in which the deformation bands develop change character and orientation as a function of i) structural position and ii) lithology, ranging from west-dipping reverse faults to conjugate sets of ladder structures (i.e. Riedel systems) as well as bedding-parallel deformation band clusters. Complex arrays of deformation bands are only present when the forelimb dip surpasses 40 degrees.

The temporal evolution of the deformation band arrays can be divided in two stages: i) in the first stage, deformation bands are controlled by lithological contrasts and boundaries of the unit, forming first along bedding laminae and between dune set boundaries; ii) in the second stage, bands develop as conjugate sets of ladders across bedding and dune sets.

In-situ probe permeameter measurements reveal host rock permeability in the range of 1000-3600 mD, whereas deformation band permeabilities are up to 2.5 orders of magnitude lower. Based on harmonic average calculations we estimate that in the forelimb of the monocline, effective permeability is reduced by a factor ranging between 3 and 40, depending on the host rock to deformation band permeability ratio. The observed arrays of deformation bands may therefore, if set in a subsurface reservoir setting, represent significant baffles for hydrocarbons and injection fluids. This suggests that where forced folds are present in subsurface reservoirs, it is important to assess sub-seismic reservoir heterogeneity such as seen in the present example. A reservoir model fed by the observations presented herein is being developed to investigate the effect of the deformation bands on simulated production performance and flow dynamics.
**Location Map:** San Rafael Reef monocline (eastern limb of the San Rafael Swell), Utah.

Detail of deformation bands in a ladder structure (Zuluaga, 2011)

Aerial photograph of the monocline (steepest segment narrower) Viewing North (Fossen, 2012)
Burlington House

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Ground Floor Plan of the Geological Society, Burlington House, Piccadilly