Small to Subseismic Scale Reservoir Deformation

29-30 October 2014

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#Subseismic14
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## POSTER PROGRAMME

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Oral Presentation Abstracts
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Wednesday 29 October
Session One: Deformation Bands
Keynote Speaker: Subseismic Deformation Structures in Porous Sandstones

Haakon Fossen¹ and Roger Soliva²

¹University of Bergen, Norway
²Université Montpellier II, France

During deformation of highly porous sand and sandstones, sets of tabular structures known as deformation bands tend to develop. These structures, particularly those involving grain comminution, contrast to fractures by being mechanically strong, having lower displacement-length ratios, and by reducing porosity and permeability. Their influence on fluid flow and reservoir performance depends on their petrophysical properties relative to those of their host rock, their thickness, abundance, distribution, orientation and connectivity. Since they are subseismic by nature, detailed information about these properties is best gathered from cores and outcrops.

Outcrop studies show that deformation band formation is very sensitive to lithologic variations, including variations in grain size, mineralogy, and porosity. Externally, the state of stress can be important, not only with respect to overburden and far-field stress that relate to tectonic regime, but also strain-induced stress related to boundary conditions. Hence the distribution and frequency of bands differ for sandstones that have undergone flexural slip, bending, layer parallel shortening, layer-parallel extension, overthrusting and fault-propagation folding. Again, we can get information about this from field examples from various settings, and some examples are presented here.

The ultimate goal of such studies is to be able to predict not only the type of deformation bands present in a reservoir, but also to say something about their frequency and distribution, based on seismic imaging, tectonic setting and lithologic information.

Deformation bands forming conjugate sets in Entrada Sandstone (Utah). These extensional bands are best developed in the upper coarse-grained and highly-porous sandstone layer.
Understanding the Distribution and Impact of Small-Scale Deformation-Band Features on Permeability and Fluid Flow in Permo-Triassic Sandstones from the UK.

A.E. Milodowski¹, J.C Rushton¹, M Hall², A.S. Butcher³, T. Kearsey⁴ and A.J. Newell³

¹British Geological Survey, Nottingham, UK
²Faculty of Engineering University of Nottingham, UK
³British Geological Survey, Wallingford, Oxfordshire
⁴British Geological Survey, Murchison House, Edinburgh

Deformation bands (sometimes referred to as “granulation seams”) are commonly encountered in the Permo-Triassic red-bed sandstones of the United Kingdom. These shear-related features are closely associated with faulting, although individual features may show only millimetre-scale or no discernible displacement. They are typically of the order of a few millimetres in width, although they may form wider zones comprised of several anastomosing deformation bands. Although their vertical development is often confined within specific bedding horizons, they may be laterally-persistent for up to 100m or more. The deformation bands are often most readily observed at outcrop in clean, well-sorted aeolian sandstones; where being often much harder than the adjacent host rock, they weather proud of the rock surface. In some cases these small-scale discontinuities may represent the only expression of faulting within these sandstone units. Although less obvious they have also been identified in core samples of muddier, poorer-sorted fluvial sandstones. The petrography and porosity characteristics in examples of deformation bands from the aeolian sandstones of the Penrith Sandstone (Permian) and Helsby Sandstone Formation (Triassic), and from the fluvial St Bees Sandstone Formation (Triassic) have been analysed, together with evaluation of their distribution in relation to faulting at the outcrop and borehole scale. High-resolution backscattered electron (BSEM) and cathodoluminescence imaging (SEM-CL) of polished thin sections shows that in the aeolian sandstones these discontinuities comprise sharply-defined (millimetre width-scale) bands of finely-comminuted detrital sand grains, tightly cemented by interstitial pore-filling quartz cement. Several generations of quartz cement may be present. Deformation bands in more poorly-sorted fluvial sandstones tend to lack quartz cementation, and instead are dominated by interstitial clay matrix. In both cases, thin-section petrography indicates only very limited microporosity. X-ray CT imaging reveals that although these features may be less than 1 mm wide, there is virtually no significant interconnected porosity across these features, in contrast to the highly interconnected pore network in the adjacent host rock. This is confirmed by micropermeametry measurements, which demonstrate that deformation bands have very low permeability in contrast to the bulk host rock. Observations show that these small-scale features have acted as significant barriers or baffles with regard to both fluid flow and geochemical transport during diagenetic alteration. Consequently, they will be potentially important to understanding the present-day fluid flow in faulted Permo-Triassic sandstone reservoir and aquifer systems.
Characterisation and Impact of Deformation Bands in the ACG Field, Azerbaijan

Seb Turner and Michael Bowler, BP Exploration & Production, Sunbury on Thames, Middlesex TW16 7BP

Deformation bands are small-scale structural features that form in porous reservoirs and can act as baffles to the flow of oil and gas. Individual deformation bands are typically a few millimetres wide and up to several metres in length, but can form intricate networks or swarms that significantly affect the effective permeability of the reservoir, having an impact on recovery rates and sweep efficiency. Core and well log data from the fluvial-deltaic clastic reservoirs of the supergiant Azeri-Chirag-Gunashli (ACG) Field, offshore Caspian, Azerbaijan, have indicated the presence of localised swarms and networks of deformation bands. The deformation bands are associated with the formation of the ACG anticline in a transpressional setting during the Late Cenozoic, and are typically clustered in parts of the structure associated with high strain, including areas of steep structural dip or tight curvature (‘hinge zones’). A similar relationship has also been observed at analogous onshore outcrops of the reservoir formations. Measurement and restoration of deformation bands from ACG cores has provided a dataset from which to build discrete fracture network models and subsequent ultra-fine scale reservoir simulation models, which permits an estimation of the impact on effective permeability and sweep efficiency across a given rock volume. This has proved valuable in siting future wells in structurally complex parts of the field, and for contemplating different recovery mechanisms.
Reducing Subsurface Risk and Uncertainty Associated With Fracturing In Intra-Volcanic Settings through Field-Based Studies and High-Resolution FMI Images

B.G. Raithatha¹, K.J.W. McCaffrey¹, R.J. Walker², R.J. Brown¹, G. Pickering³ and S. Lumbard³

¹University of Durham, Department of Earth Sciences, Science Labs, Durham, DH1 3LE, UK
²University of Leicester, Department of Geology, University Road, Leicester, LE1 7RH, UK
³OMV (UK) Limited, 14 Ryder Street, London, SW1Y 6QB, UK

Hydrocarbon exploration in frontier regions has made a series of discoveries within intra- and sub-volcanic basins along the NE Atlantic margin. Basins along this margin are blanketed in varying thicknesses of basaltic lava flows and volcaniclastic sequences, although where fluvial activity was dominant between effusive phases of volcanism, a complex interplay between basaltic lava and siliciclastic units is observed. The presence of these repeated sequences of lavas degrades the resolution of conventional seismic data (the ‘sub-basalt’ problem, e.g. White et al., 2003) leading to greater uncertainty regarding the locations of hydrocarbon accumulations and faults in the subsurface. Additionally, the architecture and lateral continuity of the lavas is difficult to predict, and the presence of different volcanic facies such as pillow lavas and columnar jointed lavas, contributes to the risk associated with drilling and further complicates the construction of reliable reservoir models. Due to the presence of this complex interplay of lithologies, fault detection and interpretation in intra and sub-volcanic reservoirs has always been a major challenge, and therefore a new approach to constraining their location in the subsurface is required.

Volcanic reservoirs exhibit a wide variety of natural fractures which vary in different volcanic lithofacies. The identification and interpretation of fractures and the extraction of fracture attributes (e.g. orientation, fracture density and aperture) from conventional logs alone is difficult. In this study, we incorporate high resolution Full-bore Micro scanner Images (FMI) and conventional well logs to produce a robust characterization of the fractures and volcanic lithofacies present in a West of Shetlands oil field. To validate the interpretation, the FMI and conventional well data were calibrated against sidewall cores and cored intervals. Where this data were unavailable, field analogues from the Faroe Islands and Iceland were used (Figure 1).

FMI and conventional log analysis indicated the presence of a variety of subaerial and subaqueous volcanic lithofacies in the studied field, such as pillow lavas, hyaloclastites, peperites and vesicular basaltic flows. Where possible, the units were correlated in other wells to gauge the lateral extent and change in thickness. As each of these volcanic lithofacies exhibits a different fracturing pattern (e.g. cooling joints, randomly oriented fractures), their identification was vital for predicting fracture distribution in the reservoir. Detailed analysis of well data also suggests that fracture distribution in the field is lithology controlled, and a result of either early diagenesis (e.g. cooling joints), tectonic activity (tensile and shear fractures) or a combination of both (e.g. reactivated cooling joints). These observations along with fracture attribute data obtained from the FMI logs were integrated with high resolution attributes derived from seismic data to evaluate the possible location of faults in the subsurface. This workflow has been successfully implemented in carbonate and clastic reservoirs and is frequently used.
to predict inter-well fracture pathways, improve history matching, and to optimize production. However, it is a novel approach in the West of Shetlands, where none of the intra- and sub-volcanic reservoirs has started producing.

Figure 1: An example of how field analogues from the Faroe Islands were used to validate FMI interpretation and help understand what environments the units may have formed in. The photo shows a ponded lava flow in the Faroe Islands with (a) Columnar Jointing and (b) Pillow lavas. The images on the right also show columnar joints and pillow lavas, but in borehole image logs. (Photograph courtesy of Simon Passey; CASP).

In this study we successfully demonstrate how datasets of different resolutions (millimetre to kilometre scale) were used to identify and interpret volcanic lithofacies and the fractures associated to them. We also show how the data can be used for predicting fracture patterns in the subsurface and ultimately constraining the location of bigger faults. However, due to the complex interplay of volcanic, volcaniclastic and siliciclastic units, the challenges, uncertainties and risks associated to them are high and therefore caution must be exercised when working with the models. We also emphasize the need for a thorough understanding of their geometries, lateral variation and emplacement mechanisms because they contribute in fault and fracture distribution and ultimately the distribution of fluid in the reservoir.
Predicting the Sealing Potential of Carbonate-hosted Normal Fault Zones

E. A. H. Michie¹,², T. J. Haines¹, J. E. Neilson¹ & N. E. Timms³

¹School of Geosciences, University of Aberdeen, Aberdeen AB24 3UE UK
²Presently at Badley Geoscience Ltd, North Beck House, North Beck Lane, Hundleby, Spilsby, Lincolnshire, PE23 5NB
³Department of Applied Geology, Curtin University, Perth, Western Australia

Analysis of selected carbonate-hosted normal fault zones on the island of Malta has been carried out to understand fault rock production and its impact on a fault’s sealing potential. Studied fault displacements range from 0.52 m up to 90 m, which has allowed systematic investigation of the evolution of fault rock types and distribution with increasing fault displacement. The focus of this study has been on locations for fault rock production, because this has significant implications for fluid flow pathways across and along fault zones, and the types of fault rock produced. The location of fault rock is dependent on the fault zone architecture. Fault zones on Malta have architectures with multiple slip surfaces within weaker carbonate layers in all fault zones above 1 m displacement, distributing fault rock onto several slip surfaces. This distribution prevents production of a continuous fault core, particularly at lower displacements, causing these fault zones to be transmissive, allowing fluids to flow across the fault. The sealing capacity is also a function of the deformation mechanisms active in the production of fault rocks. Lithological heterogeneity in a faulted carbonate succession leads to a variety of deformation mechanisms, and this can generate several different fault rock types with a range of deformation microstructures along a single slip surface. The type of fault rock produced is a function of the host rock texture. Each deformation microstructure has different porosity and permeability values, causing fault rock petrophysical properties to range from 0.0001 mD to >1000 mD permeability and 1.6% to 34.7% porosity. The porosity and permeability of the fault core will, therefore, vary along strike and down dip on any single slip surface. Details of the fault zone architecture, distribution of fault rock and types of fault rock will not be resolvable on a seismic scale. Hence, analysis from fault zone outcrops can be used to advance the predictability of these features, which are essential when considering fluid flow across and around faults in carbonate lithofacies.
Wednesday 29 October
Session Two: Modelling, Fluid Flow and Geomechanics
Keynote Speaker: Scale-dependent Strategies for Modeling the Impact of Seismically Unimaged Deformation Features

Steve Naruk¹, JP Brandenburg², Dian He¹, David Kirschner¹, John Solum³ and David Wolf¹

¹Structural Geology Research Team, Shell International Exploration and Production, Inc.
²North America Regional Exploration Team, Shell Exploration and Production Inc
³Carbonate Research Team, Shell Global Solutions, BV

“Subseismic” is widely recognized as a relative term. Subseismic deformation features having significant impact on well and reservoir performance may range in scale from cm-scale fractures or deformation bands, to meter-scale structures in shallow, high resolution seismic data, to hundreds of meter scale structures in steeply dipping beds (e.g., overturned fold limbs) and deep subsalt structures. Consequently, different modeling approaches and strategies must be adopted for modeling the impact of subseismic (i.e., unimaged) deformation features, depending on their scale, distribution, and the resolution of the seismic data.

For the steeply dipping to overturned fold limbs characteristic of fold-thrust belts, the algorithms relating fold shapes to fault geometries and displacements can be used to forward model the un-imaged portions of structure based on the well-imaged portions.

For deep subsalt structures, faults may have a hundred meters of throw but still be un-imaged. In these cases, analogs can be selected based on the suspected tectonic evolution and deformation path of the salt body. Different scenarios can be modeled to determine the potential impacts of the various analogs on reservoir performance.

Faults represent an interesting case because the locations and displacements may be well imaged, but the gouges which control the seal capacity and transmissibility are not seismically imageable. Hence the gouge properties (capillary entry pressure, permeability, thickness) must be estimated with proxies such as Shale Gouge Ratio, based on the fault displacement, wall rock composition, and potentially the burial, pressure, temperature, and deformation histories of the fault and reservoir. Additionally, there are always uncertainties around fault displacement, cutoffs, and fault zone heterogeneity along the fault zone and its associated damage zone. In this case, probabilistic scenarios can be modeled to constrain the ranges of impact of the subseismic features.

The reservoir impact of deformation bands and fractures, the ultimate “subseismic scale” features, must be represented through combinations of proxies such as strain or seismic attributes, and effective properties such as effective permeability. The proxies in turn must be calibrated with outcrop and/or core data in order to define the relationship between the cm-scale features, and the seismic-scale proxies (for example, deformation band intensity with seismic-scale strain).
Deformation Bands and Their Impact on Fluid Flow in Sandstone Reservoirs: The Role of Natural Thickness Variations

Rotevatn, A., Sandve, T.H., Keilegavlen, E., Kolyukhin, D. and Fossen, H.

1Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway
2Centre for Integrated Petroleum Research, Uni Research, PO Box 7800, 5020 Bergen, Norway
3Department of Mathematics, University of Bergen, Johannes Brunsgate 12, 5008 Bergen, Norway

Cataclastic deformation bands, which are common in sandstone reservoirs and which may negatively affect fluid flow, are generally associated with notable thickness variations. It has been suggested previously that such thickness variations represent an important control on how deformation bands affect fluid flow. The effects of such thickness variations are tested in the present work through statistical analysis and fluid flow simulation of an array of cataclastic deformation bands in Cretaceous sandstones in the Bassin de Sud-Est in Provence, France. Spatial outcrop data are statistically analyzed for incorporation in flow simulation models, and numerical simulations are used to investigate the effects of notable thickness variations on how the deformation bands influence effective permeability and flow dynamics. A suite of simulations is performed using a combination of fine-scale and coarse-scale grids, revealing that the effective permeability of the simulated reservoir is reduced by a factor of 15-25. More interestingly, the simulations further demonstrated that, as compared to the overall effect of the deformation band array on fluid flow, thickness variations along the bands proved to have negligible effects only. Thus our simulations indicate that the configuration and connectivity of the deformation bands, together with the permeability contrast between the bands and the host rock and the mean band thickness, are the most important controls on the effective permeability. Our findings represent new insight into the influence of deformation bands on fluid flow in subsurface aquifers and reservoirs, indicating that thickness variations of individual deformation bands are of less significance than previously thought.
Influence of Deformation Band Fault Damage Zones on Subsurface Fluid Flow

Dongfang Qu\textsuperscript{1, 2}, Jan Tveranger\textsuperscript{1, 2}

\textsuperscript{1}Centre for Integrated Petroleum Research (Uni CIPR), Allégaten 41, N-5007, Bergen, Norway
\textsuperscript{2}Department of Earth Science, University of Bergen, Allégaten 41, N-5007, Bergen, Norway

Fault damage zones in porous sandstones with porosity higher than 12% -15% are characterized by the presence of deformation bands which are millimeter-thick tabular bands. Forming complex networks, deformation bands may cause order-of-magnitude permeability reductions and impact subsurface fluid flow. Given recent advance in explicit fault zone property modeling, the heterogeneity and anisotropy introduced by the deformation band damage zone features such as deformation band density distributions, deformation band patterns and orientations related to extensional faults can now be captured in reservoir models. However, some features have large uncertainties and their impact on the fluid flow is not clear yet. The objective of this study is to investigate the influence of deformation band fault damage zone features on fluid flow and find out the parameters that most affect the flow simulation response.
Keynote Speaker: An Integrative Model of Strain Localization in Porous Sandstone as A Function of Tectonic Setting, Burial and Material Properties

Roger Soliva¹, Gregory Ballas¹, Haakon Fossen², Alexandre Chemenda¹ and Christopher Wibberley³

¹Université Montpellier II, France
²University of Bergen
³Total

We combine a thorough structural and petrophysical analysis of multiple deformation band sets (France, USA, Germany) with a broad dataset synthesis of deformation band permeability from the literature. Our analysis first reveals that strain localization in porous sandstones is characterized by fault zones surrounded by sets of shear bands showing a high degree of comminution. In contrast, distributed strain, where it occurs at the basin scale, does so in the form of pervasive and closely spaced compactional shear band and shear-enhanced compaction-band sets, showing moderate and low degree of comminution, respectively. Shear strain localization is inherent to the normal fault Andersonian regime and locations of upward-propagating underlying faults. In contrast, compactional strain distribution is inherent to thrust fault Andersonian regime. A synthesis of band permeability data reveals strong permeability decrease with the increase of comminution, especially in the normal fault regime. This demonstrates a major control of tectonic setting (extension/contraction) on fluid transmissibility of porous sandstones reservoirs containing cataclastic band networks. To explain this major role of remote stress conditions, we estimate the yield strength and the stress evolution in extensional and contractional regimes in a frictional-porous granular material. On the basis of field data, mechanical analyses and broad-petrophysical dataset synthesis, we propose a model of structure and permeability of deformation band network as a function of tectonic stresses, burial depth and material properties.
Impact of Sub-seismic Scale Fault Rock Properties on Fluid Flow in Penguin’s C Field, North Sea

Kachi Onyeagoro and Jorrit Glastra, Shell

The ability to predict the impact of faults on sweep efficiency and producible hydrocarbon is critical for optimal well placement, reservoir management, and field development decisions in Penguin Cluster Assets. Fault transmissibility derived from lateral connectivity between compartments and changes with depletion was recognised as key subsurface uncertainty in the field. Therefore, structural logging and analyses (fault tip extensions), microstructural and petrophysical property analyses were carried out on cores obtained from 2 wells in the field, in order to assess their impacts on hydrocarbon recovery. Disaggregation seams in sandstone, Phyllosilicate framework faults and Clay-rich slip surfaces (clay-smears) in mudstone were identified and characterised in the cores, as the 3 predominant types of faults. In particular, Phyllosilicate framework faults constituted more than 95% of the fault rocks.

Results of the sub-seismic fault characterisation and structural analyses were integrated into a Penguin C structural modelling and dynamic fault seal project to aid in understanding the current production behaviour, and predict possible infill locations. The Petrel Fault Transmissibility Multiplier plug-in was used for scaling-up and modelling the fault properties obtained from cores into a 3D framework. The modelling effort involved using the Penguin C Petrel 3D Static reservoir models, underpinned by measured fault properties from Rock Deformation Research (RDR, 2000) on Brent and Triassic reservoirs. The result of this work showed that the majority of the faults will act as strong baffles in production timescale, however, low, base and high fault permeability and fault thickness parameters were selected for dynamic simulations.

Dynamic simulation sensitivities carried out with the range of potential fault properties bracketed the historical production behaviour observed in the field. The dynamic simulation model was then used to explore the interaction between the fault property uncertainty and the other key uncertainties in the field. Using the historically observed data (production, pressures) the uncertainty ranges for the fault properties were constrained and a suite of history matched models created to allow optimisation of potential infill well locations.
Near Wellbore DFM Modeling and Two-Phase Flow-Based Upscaling of a Layered Naturally Fractured Carbonate Reservoir

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Natural open fractures represent one type of small-scale deformation structures which could have significant impact on reservoir fluid flow. Naturally fractured reservoirs (NFRs) are commonly modelled using discrete fracture Network (DFN) models in combination with dual continuum simulation. Discrete Fracture and Matrix models (DFM) offer an alternative way to the standard DFN – dual continua workflow. DFM modelling uses a boundary representation technique using non-uniform rational b-spline surface entities (BREP-NURBS) and an indirect spatially adaptive meshing approach; fractures and rock layers are gridded simultaneously with unstructured grids (Paluszny et al. 2007). Numerical simulation with DFMs is currently the only way to evaluate local balances of viscous, gravitational, and capillary forces in NFRs on the intermediate scale. Sophisticated simulation approaches, such as hybrid Finite element and finite volume methods (FEM-FVM) methods, with specific provisions to capture saturation discontinuities at fracture-matrix interfaces, are required to achieve this goal (Nick and Matthäi 2011). DFM multiphase simulations yield fracture-matrix saturation functions that can potentially explain and predict recovery and breakthrough in pervasively fractured rock with matrix permeabilities as low as a few milli-Darcies.

A sector model of a fractured carbonate reservoir, including fractures on several length scales (diffuse fractures and sub-seismic fault zones) as well as facies variations in the limestone matrix, was studied by Jonoud et al. (2013). Stochastic sub-seismic faults with enhanced permeability were introduced to match production and water-cut data. This analysis showed that industry standard fracture workflows and upscaling techniques (Snow, 1969; Oda, 1985) have severe limitations in capturing the heterogeneity and degree of flow focusing induced by the multi-scale fractures.

In a new study on the same model, the DFM approach is applied in a near wellbore setting, to improve the fluid flow modelling. The original detailed fracture and matrix characterization is honoured, and geometrically and geologically consistent DFMs are built for nine reservoir zones intersected by the well, using a new methodology for model construction and gridding. Post-processing routines are applied to obtain more realistic fracture networks, by considering stress shadow zones and removing collocated fractures. These DFMs are interrogated for their equivalent permeability, fracture-matrix flux ratio, flow velocity spectra and saturation functions, allowing for cross-layer flow between subzones (Figure 1). For the same matrix and fracture properties as in the original DFN/dual porosity approach, we obtain equivalent permeability up to 4 times higher than calculated earlier using Oda’s method. These results highlight the importance of cross-layer flow induced by the presence of multi-bed fractures and by the additional degree of connectivity, at the bed boundary, between two intersecting bed-confined fractures of different sets (Milliotte et al. 2013). This behaviour is commonly not captured by standard DFN workflows.
The new DFM model also addresses the impact of in situ stress on the fracture aperture distributions applying Cruikshank’s (1991) semi-analytical fracture aperture model and additional treatments for closure apertures. Upscaled relative permeability curves for the fracture–matrix ensemble are obtained, using the alternative fracture aperture distributions and different injection rates, following the methodology of Matthäi et al. (2012). These curves can be used in the field-scale NFR simulation.

The cross-disciplinary, multi-tool modelling and simulation approach we apply here aims to capture a maximum of geological features of NFRs consisting of layered carbonates.

Figure 1: Streamlines (dark blue curves) routed forward and backward from the centre point (white cross) of the model, following Darcy velocity vectors, through a DFM model. The model consists of 4 layers and 2 sets (grey semi-transparent surfaces, displayed only around the streamlines) of bed-confined fractures (a sub-set of the model analysed by Jonoud et al. 2013). Streamlines are jumping across sub-layers at the intersection of bed-confined fractures, at layer boundaries, in this left to right single-phase flow simulation.

References


Snow, T.D, Anisotropic permeability of fractured media, 1969, Water Resources Research, Vol. 5 No. 6, 1273-1289
NOTES
Thursday 30 October
Session Three: Imaging, Digital Rocks and Experimental Testing
Keynote Speaker: Prediction of Sub-Seismic Faulting In Hydrocarbon Reservoirs Using Stochastic and Geomechanical Modelling

Paul Gillespie, Statoil ASA

Subseismic faults are important for reservoir production both in sandstone reservoirs, in which faults act as barriers, and in fractured reservoirs in which faults act as conduits. A range of different techniques can be applied according to the data available and according to the degree of understanding of the causative mechanisms for subseismic fault development.

The simplest approaches to modelling subseismic faults use the statistics of the size and orientation distributions alone. The size distribution may be known for the larger, seismically resolvable faults and it may be possible to extrapolate the fault size distribution down to subseismic scale, typically using power-law statistics. The orientation distribution of the subseismic faults can be assumed to be similar to that of the known seismic faults. Well data, such as core and borehole image logs may provide additional constraint.

The difficulty of such a purely statistical approach is that the position of the faults is unconstrained as so is typically modelled by a random process. Alternatively, geometrical constraints may be used such as relationship to horizon dip or curvature if such a relationship can be established.

If geometrical techniques are not sufficient, then mechanical modelling can be used. In one approach used in rift settings, the larger faults are added to a boundary element model and the stress perturbations related to their movement are calculated using the assumption of linear elasticity. The stress field is then used to constrain subseismic fault position and orientation and the faults are added stochastically. This technique can produce realistic subseismic fault systems.

In a further development, the subseismic faults are allowed to grow and mechanically interact. The stress field over the reservoir is first modelled using a technique appropriate to the tectonic setting. The faults are then allowed to grow to relieve the stress field, and parameters are used to represent the rate of fault growth and the fracture toughness of the reservoir. Examples are shown of salt domes in which the stress field is modelled using the theory of elastic plates and arrays of radial and concentric faults grow spontaneously to relieve the stress. The advantage of this method is that the faults form a realistic connected network and so give a plausible estimate of reservoir compartmentalisation.
Pore Fabric Characterization of Deformation Bands and Un-Deformed Matrix in North Sea Chalks: A Novel Application of FIB-SEM Imaging and Digital Rock Physics

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Given the micron – to nanometer – scale of grains and pores of Upper Cretaceous North Sea chalk reservoirs, standard hand sample examination and optical petrography are insufficient to identify and quantify pore volumes and pore types. This limitation hinders full description of the pore system (i.e. relationship between depositional facies, diagenesis, and compaction / deformation with pore types) as it relates to rock properties (porosity, permeability, Pc behavior, etc.). Standard SEM imaging of rock chips is unable to adequately characterize chalk pore systems as rough chip surfaces alias plucked and fractured / split grains with porosity. To emulate a thin-section surface at SEM magnifications, nanometer – relief surfaces need to be polished or milled from the sample. Recently, ion milling technology has been applied in studies of unconventional and tight reservoir characterization because extremely low relief surfaces can be achieved. Thus, it is now possible to clearly image and quantify in 2-D and 3-D nanometer – scale porosity and grains in tight rock samples.

An added benefit of the ion milling approach is that milled surfaces can be generated down through the sample, revealing deeper layers for imaging. These imaged layers can be merged and a 3-D cube of the rock is generated. This approach (Focused Ion Beam (FIB) SEM imaging), reveals three-dimensional details of the rock fabric and allows for the unambiguous quantification of bulk porosity and the pore network (pore body and pore throat sizes) in the sample. From these pore geometry data, absolute horizontal and vertical permeability can be calculated through Digital Rock Physics (DRP) computations. Using more complex porous media modeling approaches, other typical SCAL properties can be calculated, including capillary pressure, relative permeability, and electrical and acoustic properties. Published results comparing this DRP approach for generating SCAL data with traditional laboratory analyses show good correlation.

One of the significant issues with North Sea chalk reservoirs is characterizing and quantifying the impact of deformation bands on porosity. Deformation bands of various types are common to pervasive in the highly porous uppermost Cretaceous chalks of the North Sea. However, characterizing these deformation bands and comparing them to the surrounding un-deformed chalk matrix has been problematic due to the extremely small grain and pore sizes characteristic of the chalk. Thus, the FIB – SEM workflow is most appropriate for this task.

Porosity, permeability, and pore size distributions were obtained from FIB-SEM analysis for both a sample in a deformation band as well as in adjacent rock (within 500 μm of the deformation band). Preliminary analysis of the sample from within the deformation band indicates that cataclasis has occurred as evidenced by the smaller sizes of grains and lower pore volumes relative to the adjacent un-deformed rock (Fig. 1). Extending this 2-D slice to a 3-D volume supports this observation (Fig. 2). Porosity calculated from these 3-D volumes shows a 30% (11.5 p.u.) reduction in pore volume (φmatrix = 38.5% vs. φdeformation band = 27.0%)
in the deformation band relative to the adjacent matrix, quantifying the visual comparison. Calculated permeabilities are an order of magnitude less for the deformation band versus the matrix (k_{matrix} = 2.8\text{md} \text{ vs. } k_{deformation \ band} = 0.25\text{md}), supporting the notion that the reduction in pore volume has a significant impact on the pore geometry and flow capacity of the deformed chalk. Examination of the pore size distributions (Fig. 3) shows that not only is the median pore size smaller in the deformation band \( \text{PD}_{\text{matrix}} = 0.774 \, \mu\text{m} \text{ vs. } \text{PD}_{\text{deformation \ band}} = 0.226 \, \mu\text{m}, \) but that the larger pore diameters are preferentially eliminated as indicated by comparing data from the samples. Thus, the deformation process does not reduce the pore volume by reducing each pore class by some uniform factor resulting in a simple shift in the distribution of pore classes but instead by preferential collapsing large pores. This reduces the variance of pore sizes generating a more leptokurtic distribution compared to the more normal distribution in the matrix. This loss of the larger pore classes has a dis-proportionate impact on pore connectivity and flow behavior, thus even though deformation bands can have a significant effect on bulk porosity, their impact on flow behaviors such as injectivity, drainage and recovery may be more significant.

Figure 1) 2-D SEM images of chalk samples from a deformation band (A) and adjacent un-deformed matrix (B). Note significant reduction in grain size and pore volume in the deformation band compared to the matrix.
Figure 2) 3-D FIB – SEM images of deformation band (A) and adjacent un-deformed matrix (B). In this rendering white is mineral matter (calcite), gray is residual hydrocarbon, and black is porosity. For petrophysical calculations, the residual hydrocarbon was included with porosity. These volumes were used to calculate rock properties (porosity, permeability, pore size distribution).

Figure 3) Comparison of pore sizes in matrix (red) versus deformation band (blue). Note that not only the median pore diameters shifted, but the range of pore diameters has decreased within the deformation band sample, resulting in a narrower distribution.
Experimental Testing of Sands Used to Quantify Deformation in a North Sea Jurassic Trap.

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A classical Upper Jurassic fault block in the North Sea, the Fulla structure, show extensional faulting and shear banding in two cores, but this deformation is much localized and imposes little damage to the reservoir quality. To investigate the deformation mechanism and products, synthetic Brent Group sand is deformed in a triaxial plain strain box with pre-defined consolidation loading in the range 100-8000 kPa, simulating a burial depth of 10 to 800 m. This depth range is typical for the formation of Jurassic traps in the North Sea. The experiments demonstrate that grain rolling and grain boundary sliding is the dominant deformation mechanism at all the simulated burial depths, and this deformation has no impact on the sand quality. The experiments concur with observations from the investigated wells and strengthen an interpretation of limited reservoir damage within the Fulla structure.
Core-Scale Deformation Analysis: What Can It Tell Us?

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Over the last 20 years, a large number of studies have been undertaken to assess the microstructure and petrophysical properties of fault rocks found within core retrieved from petroleum reservoirs. Microstructural analysis provides information on the extent of cataclasis, the amount of dilation and the timing of faulting relative to the diagenetic history. Although such analysis is quite imprecise when faulting occurs after stresses are sufficiently high to result in cataclasis (5MPa) and the temperature when mesodiagenetic reactions become rapid (90°C) the results are generally very consistent with deformation histories obtained from seismic data.

A particular aim of core-based studies has been to obtain petrophysical properties (permeability, relative permeability and capillary pressure) for predicting the sealing capacity of faults and assessing the impact of faults on reservoir performance. The sealing capacity of faults is often calculated based on threshold pressures calculated from Hg injection experiments. However, there still exists a large amount of controversy regarding whether fault rocks themselves can act as capillary seals over geological time. There is far more agreement regarding the role that faults have on petroleum production; here faults can have a wide range of behaviours from acting as very effective barriers to acting as conduits for fluid flow. Microstructural examination of core material has given a very clear indication of the controls on this seemingly paradoxical behaviour.

The permeability of faults obtained from core material is now routinely used to calculate transmissibility multipliers that are incorporated into simulation models to take into account the impact of faults on fluid flow. A few key problems exist in this workflow. Firstly, multiphase flow is rarely considered despite the fact that methodologies to incorporate multiphase flow properties of faults into simulation models were established over a decade ago and more data is available on the relative permeability and capillary. Secondly, there is still uncertainty regarding how measurements conducted on subseismic faults represent the properties of fault rocks developed on seismic-scale features that are the focus of modelling efforts.

The presentation will discuss these key aspects. It will pay particular attention to: (i) stress dependence of fault permeability; (ii) multiphase flow properties of fault rocks, and (iii) differences between the properties of seismic and subseismic faults.
Geomechanical Fracture Prediction – Case Studies Calibrated by Core, Image-Log and Production Data.

Graham Yielding, Dave Quinn, Brett Freeman, Cathal Dillon, Badley Geoscience Ltd

In fields where fractures make a substantial contribution to production, it is often challenging to predict the occurrence and hydraulic behaviour of fractures between the wells. This presentation describes a fracture prediction workflow applicable to reservoirs where most of the fractures are generated as subsidiary features around a network of seismically-mappable faults.

The two major steps in the workflow are:

- to run geomechanical models to predict the small-scale fracture patterns that might be present in the reservoir between the major mapped faults, and
- to resolve the present-day *in situ* stress onto the fracture network, as a guide to possible reservoir sweet-spots.

Displacement mapping and orientation analysis is carried out on the fault network affecting the reservoir. Combining these analyses permits extraction of the bulk 3D strain tensor represented by the fault network. The displacement pattern of the fault network is then used as input to a series of elastic dislocation (ED) forward models to compute the strain pattern within the reservoir between the faults. A variety of scenarios can be used to test the sensitivity of the modelling to different values of background strain, different fault sets, and different material properties.

The outputs from the model runs comprise a variety of strain and stress measures across the reservoir surface, and also the predicted orientations of failure planes as a consequence of the stress perturbations around the faults. The results are generally found to be relatively insensitive to the material properties, but strongly dependent on the background strain and fault set used in the scenario.

To help decide between the different ED scenarios, their output predictions can be tested against several types of observations, such as imaged/logged fractures and flow-test (PLT) data at the wells, and seismic discontinuities (*e.g.* “ant tracks”) in the fault-blocks between the wells. Modelled outputs include the magnitudes and directions of the principal strain axes. Larger modelled strains are found to provide a predictor of higher fracture density as logged in wells by image-logs or core. Similarly, fracture orientations can be related to the orientation of the strain tensor via a failure criterion.

The flow response of faults and fractures is found to be dependent on their orientation in the present-day stress field, being higher for critically-stressed fractures (high ratio of resolved shear to normal stress). The calibrated ED models can produce output for the cell centres of the reservoir model, comprise proxy attributes for predicted fracture intensity, predicted fracture orientations, and a proxy attribute for relative fracture permeability (slip tendency on predicted fractures).
Natural Deformation Structures in Reservoir Rocks Investigated Using CT-Scan Imaging Techniques - Characteristics and Fluid Flow Effects

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X-ray computed tomography (CT-scan) is frequently used for non-destructive imaging and analysis of internal structures in rock samples. Both standard CT-scan and high resolution micro-CT-scan have large potential for identification of small-scale deformation structures in reservoir rocks and outcrop analogues. In our studies we have used standard medical CT-scans with spatial resolution of 0.35 mm and micro-CT-scan with resolutions down to 7 µm. The CT imaging techniques provided 3D information that is used in combination with 2D information from core/outcrop description, thin-section optical microscope and SEM. The CT and micro-CT scanning results were used for 3D analysis of fracture networks, for imaging and 3D analysis of internal heterogeneities of fault rocks and to monitor fluid flow in single and two-phase flooding experiments.

Small-scale deformation structures, including faults and other fractures are identified in the CT-scan data as aligned groups of voxels with an anomalous CT-number relative to the surrounding host rock. The group of voxels is arranged such that the voxels define a tabular to surface-like feature in 3D or a linear feature in 2D view. An open fracture contained within a voxel will result in the CT-number of the voxel being reduced compared with the surrounding rock. A cemented fracture, deformation band or small-scale cataclastic fault has an increased voxel CT-number relative to the surrounding porous media. In some cases the structural features are recognised in the CT and micro-CT-scan even without any trace of deformation features being seen on the sample by eye or using hand lens.

Deformation bands in chalk from the North Sea were investigated using CT and micro-CT-scan in combination with core description, thin-section analysis and SEM. The deformation bands are characterised by a gradual and diffuse boundary to the host rock, and they are associated with a reduction in porosity from 30 to 40% in the matrix to 10% or less inside the deformation bands.

Small-scale faults in a porous carbonate rock from outcrop are characterised by a high degree of heterogeneity and comprise volumes of reduced porosity as well as open patches. Two-phase flooding experiments monitored by continuous CT-scanning are planned to improve the understanding of the effect of such faults on flow pattern.

Fluid flow in fractured media and matrix-fracture interaction during one and two-phase flooding experiments on sandstone samples containing natural fractures has been monitored by continuous CT-scanning. Such experiments provide an effective tool for integrating geology and fluid flow properties of a porous fractured media. The experimental results demonstrate the dramatic effects of open fractures on the flow pattern, even in a case where the matrix properties are relatively good with porosity of 17 to 18 % and permeability of 200–300 mD.
Thursday 30 October
Session Four: Seismic Methods
Combining Multiple Seismic Attributes to Sweet-Spot Well Locations in Fractured Reservoirs, both Conventional and Unconventional

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Subtle sub-seismic structural features (faults, fracture corridors, karsting along faults, fault-related diagenesis and similar processes) can strongly influence well and reservoir behavior in both tight conventional and unconventional reservoirs. This influence can be in the form of drilling costs and losses, or of increased production of water and/or hydrocarbons. Given their importance from both drilling hazard and well production points of view, accurate interpretation of structural features is of first order importance. Reliable interpretation, however, is inhibited by the small size of the structural features, which is at or below seismic resolution. Interpretation reliability is increased by selectively generating multiple attribute volumes, interpreting all visible lineations on each volume, and combining the individual interpretations so that the signal of the subtle structural features is enhanced. Combining the results from multiple volumes enhances the imaging relative to a single volume; the combined attribute volumes reveal subtle features that are not apparent in any single volume (e.g., anttracker, curvature or dissemblance).

In addition to providing a more reliable structural interpretation, the combined lineations provide the input for the calculation of proxies for fracture intensity and fracture connectivity. In general, larger faults and fracture corridors contain higher fracture densities and are longer than smaller faults/fracture corridors. Azimuthal variance is used as a proxy for fracture corridor connectivity. Most significantly, these proxies can be combined with existing well production data to create empirical predictive models of well production (rates and volumes).

This technique has been applied to four fields with a direct structural control (production from subtle faults/fracture corridors) or with an indirect structural control (production from structurally-controlled diagenesis) on reservoir properties. Combination of the fracture proxies discussed above has resulted in models that predict 70%+ of producing wells and exclude 75%+ of dry holes (with each of the fields containing approximately 20 to 70 wells).
NOTES
Understanding the Imprint of Fractures in the Seismic Wave-Field

AW Roberts¹, JJ Long¹, E. Vsemirnova¹, RR Jones¹, KJW McCaffrey², RW Hobbs²

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Understanding fracture connectivity in the shallow crust is of major importance for the development and production of hydrocarbon fields. Fracture datasets collected from wells have limited spatial coverage compared to remote sensing methods such as seismic imaging, Ground Penetrating Radar (GPR), electromagnetic recording, Terrestrial Laser Scanning (TLS), and Unmanned Aerial Vehicles ("drones"). In this study we focus on understanding the imprint of a realistic 3D fracture network on the seismic wave-field.

The thin, often rough sheet-like form of fractures poses challenges for reliable imaging of fracture networks using seismic methods, and the seismic response can be significantly altered by the highly variable dip of the fractures in question. Some studies have been published showing the effect of the presence of simple fracture configurations on the synthetic seismic wave-field. At present, however, due to the inherent complexity of real rock fracture networks, there is limited understanding regarding the discernment of network characteristics from seismic data.

Our work involves forward seismic wave-field simulation of a range of complex fracture networks derived from detailed quantitative characterisation of fractures in outcrop. We aim to build a library of calibrated examples from which to both develop qualitative understanding of the information contained in a seismic dataset pertaining to the fracture network, and further research into the quantitative inversion and imaging of such information.
Multi-Azimuth 3D Seismic Imaging of a Highly Compartmentalised Reservoir, South Hammerfest Basin, Offshore Norway

Mark Mulrooney¹, Alvar Braathen² and Johan Leutscher³

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Initial single azimuth 3D seismic acquisition of the Goliat Field area in the southern Hammerfest Basin, offshore Norway resulted in significant imaging problems owing to a number of factors including the presence of three dominant fault trends, high compartmentalisation of reservoirs, dimmed areas owing to gas leakage and sea bottom glacial related morphology induced multiples. Vigorous reprocessing and resultant spatial resolution loss proved inadequate for reservoir horizon ties and fault mapping. Reacquisition using a towed streamer Q-marine multi-azimuth (MAZ) survey was deemed necessary in order to improve imaging and reduce uncertainties at reservoir levels. Azimuth values were chosen to compliment fault trends identified by earlier seismic investigations. A phantom undershoot was also conducted at the site of a future planned floating production, storage and offloading vessel (FPSO). Significant improvements in subsurface imaging resulted from the MAZ survey including the attenuation of multiples, better fault illumination and signal to noise ratio increase. The MAZ survey provides a larger azimuthal fold resolving previously invisible reservoir level reflectors. In addition to resolving the architecture of the Goliat prospect, the MAZ survey allows for detailed sediment routing and fault activity studies. Surface attribute extractions provide evidence for tectonic influences on antecedent drainage systems which help map potential reservoir quality sand bodies and fault controlled compartmentalisation. The excellent seismic resolution also allows detailed mapping of minor brittle deformation related to fault process zones and is valuable information in drilling hazard mitigation.
Keynote Speaker: The Contribution of Sub-Seismic Faults to Deformation in the Earth’s Upper Crust

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Deformation in the Earth’s upper crust is largely accommodated by brittle structures such as fractures and faults. A common observation is that the amount of extension recorded by faults in the crust is significantly lower than the extension estimated from crustal thickness and subsidence analysis. This has been explained by the contribution of ‘small-scale’ fractures and faults to crustal extension. These are often difficult to resolve in most the sub-surface, and their role in modifying reservoir behavior uncertain.

Previous attempts to extrapolate ‘small-scale’ extension, applying power-law relationships to fault size distributions, often produce unreliable estimates due to limited measurable scale ranges within datasets. The studies were specifically designed to provide direct measurement of extension on structures across a range of scales, with particular emphasis on the transition from seismic to sub-seismic displacements. A key factor in data selection was that a complete record of displacements over the range 1 – 30 m could be obtained, either by: 1) using techniques that fully sample the strain at length scales in the range 1m - 10 km and displacements of 0.1 - 100 m; or 2) hierarchical sampling that brings together data from damage zones to large faults. The data include examples of normal and strike-slip fault networks acquired by high-resolution seismic reflection surveys, multibeam bathymetry and detailed field observation. Extension was measured by using 2-D and 3-D displacement gradient tensors or by summing fault heaves on traverses at a high angle to the faults.

Results indicate that sub-seismic structures (small faults, extension fractures, deformation bands, etc.) contribute up to ~5% crustal extension, and this may be of great significance in low strain regions. At higher strains, however, seismically resolvable faults can be shown to contribute most of the crustal extension, accounting for ~80% of the total extension. This phenomena is attributed to fault growth and strain localization onto larger faults, which appears to dominate at total extension greater that ~5%.

These studies allow us to estimate extension from limited fault data, and assess uncertainties in such estimates. Whilst strain may help constrain the quantity and geometry of sub-seismic faults, their distribution also has a strong influence on properties such as deformation and fluid flow. The data can also be used to investigate the organization of fractures within a reservoir. For example, the extent and location of damage zones and the topology of fracture networks are both important in controlling fluid flow and reservoir quality.
Stylolite-Controlled Stratabound Dolomitization: Examples from the Benicàssim Case Study (Maestrat Basin, E Spain)

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Stylolites are very common subseismic-scale structures consisting of rough surfaces of dissolution. They are ubiquitous in carbonates and can be either barriers or conduits to fluid flow. Stylolites can potentially play a role in the resulting geometry and petrophysical properties of diagenetic or hydrothermal alterations, thus affecting reservoir quality. An example of such an alteration is hydrothermal dolomitization, which forms when fluids hotter than host rocks are advected and interact with limestones. These fluids are normally transported upwards along faults and then invade host limestones. Two end-member geometries can arise from this process: (1) dolostone appears in irregular patches around faults and (2) dolostone appears in preferential layers that extend away from faults. The main parameters determining the transition from one to the other are the original depositional facies distribution, pre-dolomitization diagenesis and structures (i.e. fractures and stylolites). Despite the abundance of case studies, very few have reported the influence of stylolites on dolomitization geometries, and no systematic analyses have been made.

The Benicàssim outcrop analogue (Maestrat basin, E Spain) is a world-class example of hydrothermal stratabound dolomitization. In this area, seismic-scale stratabound dolomitized bodies extend for several kilometers away from large-scale faults, replacing syn-rift Aptian-Albian shallow-marine carbonates. Field and petrographic data indicate that grain-dominated facies are preferentially replaced while mud-rich facies are less frequently dolomitized. However, grainstones and packstones crop out occasionally between dolostone layers, suggesting that not only the depositional facies determined which rocks were dolomitized. Most of the beds contain dense networks of sedimentary (i.e. layer-parallel) stylolites, as well as several sets of meter-scale fractures of different ages. Dolomitization fronts are always very sharp, and the vast majority of them weave up and down following consecutive stylolites. This suggests that stylolites acted as vertical barriers to fluid flow, and constrained the reaction to only one side of them. Stylolite density and teeth height does not dramatically change between the different layers. However, high-amplitude stylolites are found in certain muddy layers, creating anastomosing networks that acted both as vertical and horizontal barriers to fluid flow, thus constraining dolomitization.

Complementary advection-diffusion numerical simulations illustrate how fluids can be channelized depending on the geometry and connectivity of stylolite networks, suggesting that these structures can significantly control the formation of alterations such as dissolution, cementation and replacement. This contribution shows that ubiquitous subseismic-scale pressure solution structures may determine the distribution of the resulting diagenetic products of a carbonate reservoir, defining their effective horizontal and vertical hydraulic properties and hence its quality.
Poster Presentation Abstracts
Lithological Controls on Subseismic-Scale Reservoir Deformation in Upper Carboniferous Sandstones, Northumberland, UK

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Deformation patterns can be very complex at “reservoir” scales in response to three-dimensional strain, especially in faulted heterogeneous sedimentary layers. Although the regional stress field may be homogeneous, shear fractures within different lithological units are likely to display variable geometries, orientations, frequencies and displacement vectors, leading to complex subseismic-scale deformation. We analyse a system of normal faults cutting through Upper Carboniferous alluvial plain sediments that crop out on the Northumberland coast, near Hartley (UK). A thorough understanding of these sub-seismic scale deformation processes is essential to evaluating the petrophysical properties of a heterogeneous reservoir, especially in the case of Upper Carboniferous sandstones, which are a proven petroleum reservoir in the North Sea.

At Crag Point, near Hartley, an E-W trending, N-dipping normal fault brings 20m of thick aggraded channelized sandstones in the hanging-wall in contact with a heterogeneous sequence, comprising of interbedded sandstones, siltstones, shales and coals in the foot-wall. The style of deformation, in particular fault orientations and kinematics, are strikingly different in the foot- and hanging-walls of this major fault. The sandstones in the hanging-wall are deformed by a system of steep conjugate- faults (ca. 20° dihedral angle) oriented E-W or ENE-WSW and with relatively small vertical offsets (< few meters). Some faults show pure dip slip indicators, while others display sub-horizontal slickenlines. In the vicinity of major slip surfaces, intense fracturing occurs, displaying an intermediate stage of fault brecciation. In comparison, the interbedded sandstones, shales and coals from the foot-wall are deformed mainly by more gently-dipping (ca. 65°), purely extensional faults. These faults strike mainly E-W, but are associated with secondary NW-SE extensional faults. Displacement along these faults generates ductile drag and bed-parallel slip within the wall rocks, and smearing of the shales and coals along the fault planes.

Previous authors have attributed these differences in structural style to the effects of Variscan inversion, or partitioned transtension during the late Carboniferous. Nevertheless, the clear difference in structural styles observed within the channelized sandstones in the hanging-wall and the interbedded sandstone, siltstone, shale and coal sequence in the foot-wall leads us to suggest that lithology may be the primary control on structural style at Hartley. From transect orientated N-S, approximately orthogonal to the strike of the major fault, we recorded the orientation, frequency, displacement and geometries of joints, shear fractures and deformation bands in order to estimate the orientations and magnitudes of the principal strain axes within the deformed foot- and hanging-wall sequences. These datasets will enable us to test the hypothesis that the observed structures accommodate geometrically-necessary near field strains adjacent to the N-dipping normal fault, and that the variation in structural styles results from the different behaviour of lithological units to accommodate flexure and bed-parallel slip.

This study demonstrates the continuing importance of outcrop studies to develop and revise conceptual models of reservoir deformation that can be applied to the subsurface.
Application of Pyrenean Fractured Carbonate Outcrops for Reservoir Characterisation

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Fractured reservoirs such as tight carbonates are often highly heterogeneous in terms of open fracture distributions and hydraulic connectivity, so that well performance can range from very good to very poor. Observations and data collected from analog exposures, coupled with the application of sound geological principles based on field geology, minimises the risk of mis-interpretation of well or seismic data. This is especially relevant to fracture characterisation within the sub-seismic volume because of the hierarchy in scale that fracture networks show, including fracture corridors and sub-seismic faults that often have a big influence on reservoir flow properties but cannot be easily identified and mapped. In addition, the outcrop messages and geological principles underpin critical evaluation of the results of techniques such as curvature analysis and seismic attribute analysis.

This poster makes use of some excellent Pyrenean outcrops of folded, faulted and fractured Cretaceous carbonates to discuss the following issues that are commonly encountered during reservoir characterisation:

- How to evaluate the influence of mechanical stratigraphy on fracture dimension, style and distributions
- How to include sub-seismic scale fractures in conceptual and static reservoir models and flow simulations
Assessing Risk and Uncertainty Associated With Volcanic Lithofacies in the Subsurface Using Borehole Images and Well Data: Examples from the Faroe-Shetland Basin

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Intra- and sub-volcanic, hydrocarbon bearing plays in the Faroe-Shetland Basin reveal a complex interplay between inter-layered lava sequences and siliciclastic sediments. Numerous unique challenges are associated with the presence of volcanic lithologies in hydrocarbon-bearing basins ranging from seismic imaging to field development. The internal complexity and heterogeneity of different volcanic units is still poorly understood, and great uncertainty is related to their lateral distribution in the subsurface. The uncertainty related to the volcanic rocks (both sub-aerial and sub-aqueous) makes construction of reliable reservoir models difficult. Additionally, the presence of volcanic units in the basin contributes to the risk associated with drilling. Using a combination of borehole image logs, conventional core, and wireline logs from the Rosebank Field in the Faroe-Shetland Basin, we were able to: (i) identify different volcanic lithologies; (ii) determine their ability to fracture during drilling; (iii) assess their suitability as seals or potential reservoirs; and (iv) assess the nature of the contacts between the main volcanic formations and the Colsay Member sandstone intervals. In particular, we emphasize the value of FMI data in delineating key volcanic lithofacies and their associated structures, and recommend the use of datasets at multiple scales in gauging their role in fluid distribution within a reservoir.
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