# Petroleum Geoscience Research Collaboration Showcase

# 21 – 22 November 2012

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| **Helium – Exploration For An Elusive And Valuable Gas**<br>*Diveena Danabalan[1], Jon G. Gluyas[1], Chris J. Ballentine[2], Colin G. Macpherson[1]*<br>*[1]Durham University, [2]Manchester University* |
| **Petrophysical and Petrological Properties of Hyaloclastite Deposits: Examples from the Hawaiian Scientific Drilling Project (HSDP) Phase II**<br>*T. J. Watton[1], Kirstie Wright[1,2]*<br>*[1]Volcanic Margins Research Consortium, Durham University,[2] DONG Energy E & P* |

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| **Forward Seismic Modelling Of Shallow Marine Clinoforms Constrained By Outcrop Observations From The Cretaceous Western Interior Seaway, US: Analogues For The Krossfjord And Fensfjord Formations, Troll Field, Norwegian North Sea**<br>*Nicholas E. Holgate[1], Gary J. Hampson[1], Christopher A-L. Jackson[1], Steen A. Petersen[2]*<br>*[1]Imperial College London, [2]Statoil ASA* |
| **Characterisation of Fracture Systems using Subsurface Digital Outcrop Models**<br>*Thomas Seers[1], David Hodgetts[1]*<br>*[1]University of Manchester* |
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# Poster Presentation Abstracts

## Salt Tectonics in the Ling Depression, Northern North Sea: Implications for Seal Integrity

Adam Cheng, *Royal Holloway*

The Ling Depression is a structural low formed by Mesozoic reactivation of the Caledonian Hardangerfjord Shear Zone. The Lupin prospect has been identified in the Ling Depression and a drilling programme is scheduled for late 2012. The proposed reservoir-seal pair is Rotliegend Group – Zechstein Group. Understanding the distribution, evolution and structural style of the Zechstein Group is therefore a key element of understanding the risk associated with such plays. Five main phases of Zechstein Group halokinesis are identified:

1. Rifting triggered salt inflation during mid to late Triassic
2. Rifting triggered inflation/diapirism during Jurassic
3. Passive loading halokinesis in early Cretaceous
4. Extension triggered halokinesis and salt collapse in Paleocene – earliest Eocene
5. Compression triggered halokinesis rejuvenation in mid-Miocene.
6. Spatial variation of halokinesis style is also observed:
7. Passive halokinesis during early Cretaceous is only observed adjacent to the intra-Ling Depression High
8. Extension triggered halokinesis and collapse in Paleocene did not affect the SW end of the study area.
9. Complete salt weld is only observed in the SW end of the study area while large part of the study area is connected to Zechstein source layer.

Seal risk is therefore considered low for a large part of the study area. Seal integrity in the SW of the study area is uncertain because of the difficulties in quantifying the effect of salt dissolution as boundary layer theory implies complete withdrawal of salt is impossible by viscous flow alone. The collapse of salt walls in Paleocene implies a partial weld can be formed with more than 50m thick source Zechstein layer. The entrainment of non-mobile marginal evaporite facies within the Zechstein Group has probably created more boundary drag and retarded salt flow. Comparing with the salt welds and development of interpods in the South Viking Graben, it is suggested salt basin margins may pose a lesser risk for seal integrity by retarding the mobility of evaporites.

## Maturity, Rock Properties and Natural Fractures in the Bowland Shale,Bowland Basin, NW England: Implications for Shale-Gas Recovery

Hamechan Madhoo, *Royal Holloway*

The importance of unconventional shale-gas systems is evident from the success of numerous prolific shale-gas plays in the United States. Recently, interest has been focused on potential shale-gas systems in the U.K. The Carboniferous Bowland Basin of NW England has thick sequences of organic-rich shales (average TOC 2-6 wt. %), and the Bowland Shales in particular have been targeted in this respect. In 2010-2011 the Preese Hall-1 well, owned and operated by Cuadrilla Resources Ltd. drilled into and hydraulically fractured the Bowland Shales.

Understanding the maturity together with the interaction of hydrofractures with the existing natural fracture networks is essential for effective hydraulic stimulation. Therefore, this report investigates the maturity, rock properties and natural fractures in the Bowland Shales in order to establish their likely influence on shale-gas recovery.

Sonic velocity analysis and burial history modelling indicates that the Bowland Shales became mature for gas during the Jurassic – Cretaceous following early oil generation prior to Variscan inversion in the Late Carboniferous. The Bowland Shales are not currently generating gas; however, the process of adsorption may aid in the secondary cracking of kerogen and any retained oil. The *in situ* stress conditions at the hydraulic fracturing depth of 7679 – 8951 ft (2341 – 2728 m) is governed by a strike-slip triaxial stress state, where the maximum horizontal stress, $S_{Hmax}$ trends NNE-SSW to N-S and is equal to $\sigma_1$ which is ≈ 81 MPa. The vertical stress, $\sigma_v = \sigma_2 \approx 64$ MPa and the minimum horizontal stress, $S_{hmin} = \sigma_3 \approx 51$ MPa. Therefore, it is expected that hydrofractures will be vertical and propagate parallel to $S_{Hmax}$. There are at least two dominant natural fracture trends, one near-parallel to $S_{Hmax}$ and another roughly perpendicular to $S_{Hmax}$. Whilst some fractures are open, most are fully healed and predominantly calcite filled. The $S_{Hmax}$-parallel fractures tend to reactivate along their contact with the shale host rock, leaving much of the shale unstimulated. Whilst the calcite-filled $S_{Hmax}$-perpendicular fractures do not appear to arrest the hydrofractures, the open fractures do, and hence, are detrimental to effective stimulation.

It is proposed that the natural fracture population parallel to $S_{Hmax}$ may not be beneficial to effective shale-gas recovery, since their reactivation can lead to less stimulation of fresh shale surfaces where the gas is held as free gas in micro-pores and/or adsorbed to the organic matrix. It is suggested that further treatments may consider targeting less naturally fractured zones.

## The 3D Structure of the Normal Fault Zone, Kilve, Somerset and Implications for Seismic Resolution and Fluid Flow

Andrew Wrigg*, University of Leeds.*

Seismic sections at best have resolutions around 12-20m, therefore any structure smaller than this resolution such as fault throws are unidentifiable (aka sub-seismic). However sub seismic structures such as faults can play a large role in fluid flow in a hydrocarbon prospect.

Therefore by using outcrop analogues the structure and properties of smaller features not identifiable in seismic sections can be studied and therefore assess the accuracy of seismic resolution at predicting the structure of an area and the possible consequences of this for fluid flow.

The particular example used in this scenario is the excellent normal fault exposure present at Kilve, Somerset. Both structural and stratigraphic data was gathered from this area and put into the program petrel to enable the construct of a 3D fault model of the area. This model was then used to run simulations of the appearance of the structure in seismic resolution (12.5m) and in outcrop resolution (1m). These models combined with the calculations of the fault properties in basinal settings then allowed the qualitative assessment of the accuracy seismic resolution has on the structure of the area and the possible consequences for fluid flow in the area. The results show that there is a large amount of faulting in the area which cannot be imaged by seismic data, therefore seismic data is unable to resolve small scale structures.

However these sub-seismic faults may not completely block flow in a reservoir, but instead can severely restrict it, still creating possible problems during production.
The results also show that the lateral and vertical geometry of the larger seismic scale faults in seismic sections are not accurate. This is due to seismic resolution either causing the amalgamation of two proximal faults, or the early tipping out of a fault laterally due to a decrease in throw towards the tips. This imaging problem however can have large effects on fluid flow, giving geometries which may seem sealing but are in fact not and vice versa.

## 3D Analysis of Compressional Structures in the Santiago Basin, Peru

Ligia Andrea Murcia Vargas*, University of Leeds*

Compressional salt structures are a common feature within the Santiago Basin, northwest Peru. The interaction of salt bodies, the surrounding syn-kinematic sequence with characteristic terminations and changes in thickness and the occurrence of contractional syn-orogenic stresses have played a role in the resulting structures. The aim of this study is to investigate the variation in structural styles present in the basin.

Although the basin configuration is considered, three structures are investigated and form the basis of more detailed structural modelling is under the Northern structure corresponds to a passive diaper whose growth is associated with high sedimentation rates. It reached a peak stage and was subsequently compressed with the generation of a vertical weld. The Central structure is a thrusted passive diapir whose growth also involves a high sedimentation rate. The Southern structure is a former salt cored anticline which has been shortened and cut by a thrust fault causing overlapping of sequences deposited on both limbs. The study compares and contrasts the 3D evolution of each structure.

## Digital Mapping of the Late Ordovician Glacial Stratigraphy Tassili N' Ajjer, Algeria.

Robert Reglinski[1], Franklin Rarity[2], Simon Brocklehurst[2], Richard Dixon[3]

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A great deal of research has centred around the understanding of the Late Ordovician Glacial event in Northern Africa as part of on-going efforts by academic workers to understand glacial stratigraphy and glacial systems, and by industrial enterprises to unlock resources. This study aims to update the geological mapping of the Tassili N' Ajjer in southern Algeria, which represents a world class section of exposed Ordovician glacial stratigraphy that remains relatively un-mapped, due to its location. This will develop the regional understanding with the aim of helping to improve clarity within this glacial system and aid in the development of robust industrial geological models.

This study combines satellite data with targeted field studies to improve the solid geological mapping and build regional understanding. Spot 5, parent geological mapping, field work and LANDSAT™ data was overlain on a 30.9 m resolution digital elevation model of the Tassili N' Ajjer in a 3D working environment. Based on this data, a set of defining characteristics was created for each of the established geological units (Figure 1, Eschard et al. 2005). The Tamadjert was further subdivided into four geological units based on field observations (Hirst et al. 2002; Dixon et al. 2008). These units were mapped in the 3D environment and used to create a new solid geology sheet (Figure 2).

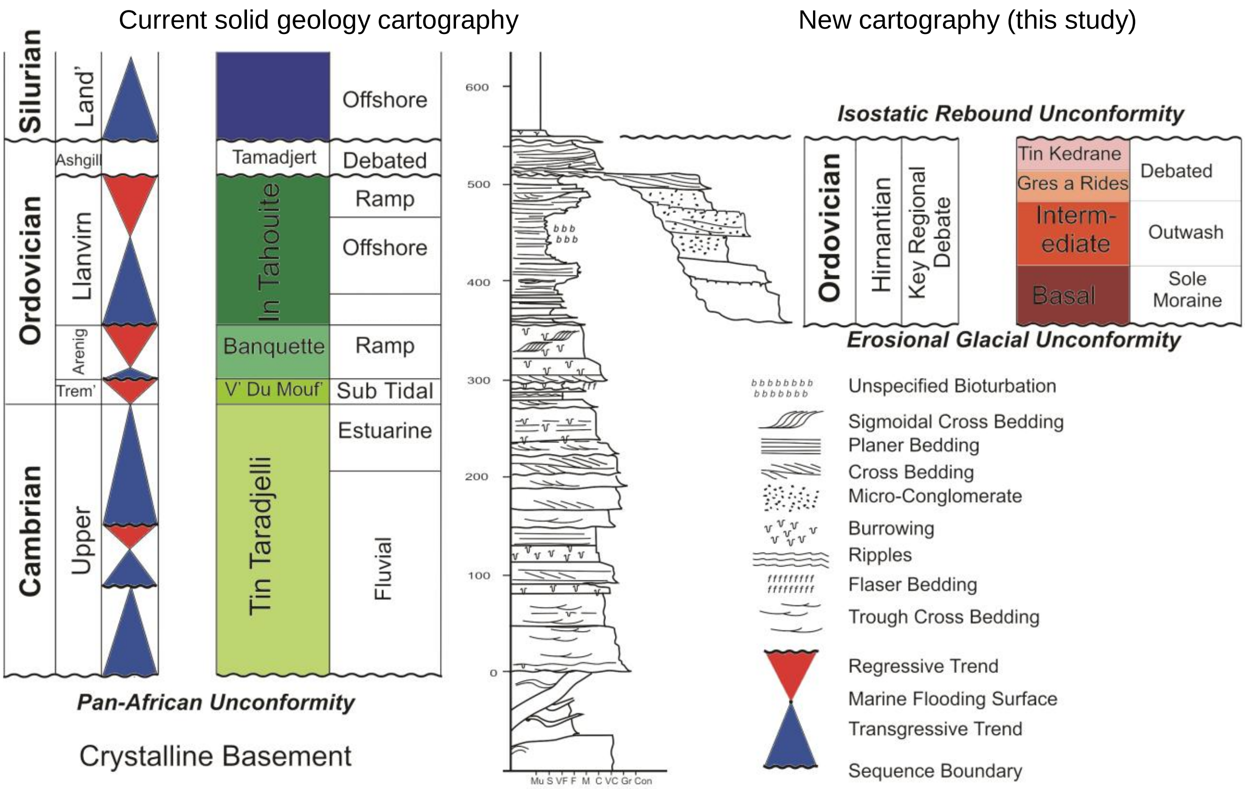


**Figure 1**: Stratigraphy of the Tassili N' Ajjer showing basis for geological mapping. Modified from Eschard et al. (2005) using Hirst et al. (2002) and Dixon et al. (2008).

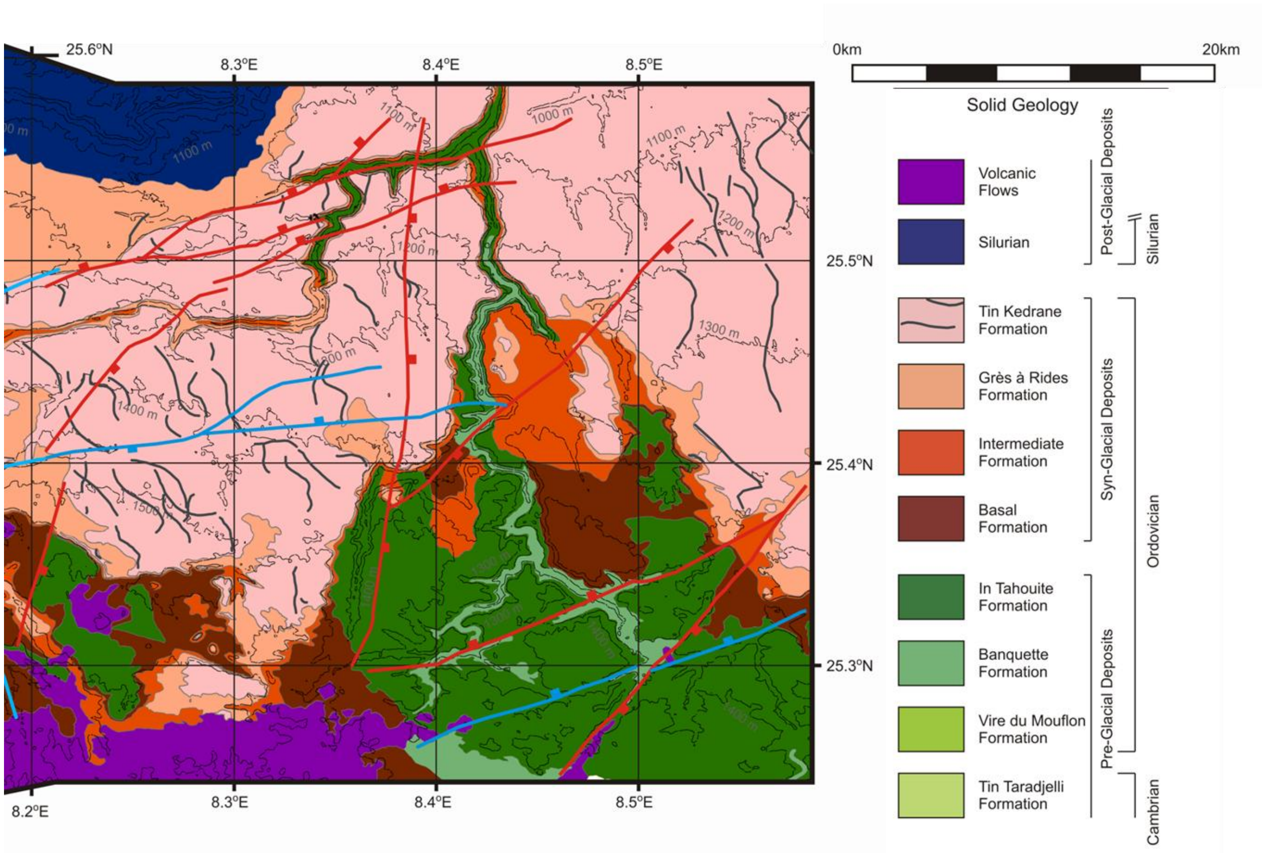


**Figure 2:** Sample of updated solid geology map. The cartographic separation of the Tamadjert Syn-Glacial deposits (brown through pink) is new to this study.

Based on grounding studies and previous literature the updated map is a very good representation of the solid geology at 1:100,000 scale. The confidence in the identification of units on satellite imagery was high considering the wealth of control data in the form of parent geological mapping, field work and photographs. The harshness of the climate in this region greatly aides this method as the outcrops are near 100 % exposure and visible from space. The extensively developed canyons and surrounding topography allows a unique ability to map in 3D, however key structural features such as folds, faults and quantitative dips are impossible to accurately understand although their sense is captured. A higher resolution data set would be required to improve this. This method would not be possible if the topography was flatter or without the superb grounding geological field work and map that preceded it.

## Numerical Modelling of Natural Fracture Propagation in Shale-dominated Sequences

St John Piano[1,2], Professor Jon Trevelyan[1,2], Dr Jonathan Imber[2,3], Dr Ken McCaffrey[2,3], Dr Richard Jones[4]

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Natural gas is sourced increasingly from shale reservoirs. Hydraulic fracture stimulation (fracking) is used to access this so-called “shale gas” cost-effectively. Fracking can reopen pre-existing natural fractures to create paths to the gas held in the shale. Gas then flows back along these paths and can be extracted. Better knowledge of the geometry of natural fractures will allow the design of more efficient hydraulic fracture systems.

Natural fracture networks observed in exposures of exhumed, shale-dominated strata are characterised by curved second-order fractures that connect larger, laterally extensive extension fractures. Our hypothesis is that curved second-order fractures result from a) heterogeneous three-dimension stress fields that develop at the intersections between sets of vertical and horizontal fractures and/or b) dynamic perturbation of the stress field during propagation of the vertical extension fractures.

This project aims to model natural fracture propagation to test this hypothesis. This modelling will use numerical techniques developed by the Mechanics Research & Teaching Group in the School of Engineering and Computing Sciences at Durham University.

## Seepage Slick Calibration of Seal Bypass Systems and *Vice Versa*

Gareth Williams[1,2], Mads Huuse[1], Christophe Serie[1], Alan Williams[3], Niels Schødt[4]

[1]*University of Manchester*
[2]*Now at ERCL*
[3]*Fugro NPA*
[4]*Maersk Oil & Gas*

This paper presents an overview of calibrated subsurface plumbing systems in a salt diaper and minibasin setting offshore West Africa, based on the integration of 3D seismic data and sea-surface satellite imagery. Salt structures on the middle slope serve a dual purpose as trap and seepage-focusing features, with traps focused on the down-dip side of overhanging diapirs and seeps located on the updip sides and flanks where strata are deformed and inclined with vertical relief exceeding two kilometres. Associated subsurface leakage phenomena include gas and gas hydrate accumulations, seal bypass systems including pockmarks, pipes and faults, depending on the structural configuration of the aquifers and aquitards that define the stratigraphically concordant parts of the plumbing system. Our analysis suggests that seismically defined seal bypass systems (pipes, pockmarks, BSRs) can be linked to seepage slicks of various degrees of confidence ranging from 99% confidence to no observed slicks, which may be explained by discontinuous seep activity or by pure gas seeps. Interpreted seepage slicks of moderate confidence may variously be underlain by well defined seal bypass systems, pockmarks with no discernible fluid migration paths, or have no seabed or sub-bottom expression at all.

## Modelling Geological Architectural Elements from 3D Seismic for development, Kasamene Field, Albertine Graben, Uganda, East Africa

Rebecca Kyokwijuka, *University of Manchester*

This poster presents an analysis of the architectural elements of the H30 reservoir of the Kasamene field. The study has employed the use of seismic attribute analysis to enhance, determine and interpret geological features, depositional environments, reservoir geometry and sand body connectivity.

The Kasamene field is a wedge-shaped extensional horst bound by a W-E fault to the north, a SSW-NNE fault to the east and a regional dip to the Southwest. Evaluation of the seismic, well data and sedimentology indicates a fluvio-deltaic depositional environment with a drainage system mainly controlled by topography, Lake water level variations, tectonics and climate. Based on well logs, the average thickness of H30 reservoir is about 37m. The reservoir sands occur as thin sheets with thicknesses ranging from 1-3m hence most of them are far below seismic resolution.

The presence of fluids (gas) in the reservoirs affect the seismic around Kasamene-1 and Kasamene-2 wells resulting in variations in reflection amplitudes which obscures most geologic features across the field. To address this, amplitude normalisation had to be done.

Depth maps constructed for key horizons indicate a regional dip to the SW into the basin. From the net-sand property model, sand geometries that represent possible channel belts generally trend in a NW-SE direction. However, wells often show very low net-to-gross especially Wahrindi-1 well; this may be attributed to high lake influence during H30 reservoir deposition. Based on well log analysis over the Kasamene field, individual channels are generally not well developed. Together with seismic analysis, this is interpreted to indicate an overbank depositional environment in this area, characterised as a crevasse splay complex.

Integration of well data, sedimentology and 3D geological modelling has enabled data ealisations which can be used for simulation to obtain appropriate and more representative development plans. The geometry, size, shape and the architecture of the reservoir facies in relation to non-reservoir facies has been assessed, to determine the field development strategy e.g. well placement, number of wells and their spacing and the type of recovery mechanism for effective production.

## Holywell Shale: Evaluating the Gas Potential

Leo Newport, Chris Greenwell, Jon Gluyas, *Durham University*

We present a geochemical and geological characterisation of the Namurian aged Holywell Shale, North East Wales and assess its potential for shale gas production. With the recent change in US gas supplies, with a significant portion met through domestic shale gas production, shale gas is increasingly being explored for in Europe. In the UK, the Carboniferous shales (specifically Namurian – 313 - 326Ma) have been the main focus. The Holywell Shale is a distant relation to the Bowland and Edale Shales, and part of the Bowland Shale Formation. The Holywell Shale has previously been studied for its potential as a source rock for the East Irish Sea gas fields and for its fossiliferous marine bands and palaeoclimate. In the present work, outcrop samples of the Holywell Shale from Flintshire have been analysed using organic matter characterisation techniques including total organic carbon, carbon isotope analysis; as well as mineralogical characterisation through powder X-ray diffraction; and, finally, porosity and adsorption analysis. Further analysis is on-going to fully understand the hydrocarbon potential of the Holywell Shale, and to identify correlations between pore space, organic matter and mineralogy.

## Gravitational Faults: Migration Pathways for Recycling Gas after the Dissociation of Marine Methane Hydrates, Offshore Mauritania

Jinxiu Yang, Richard J. Davies, *Centre for Research in Earth Energy Systems (CeREES), Department of Earth Sciences, Science Labs, Durham University, UK, DH1 3LE*

Three dimensional seismic data from offshore Mauritania (West Africa) reveal tiers of normal and tear faults that are approximately parallel to the strike and dip of the slope respectively. They formed as a result of multiple episodes of down-slope creep and have propagated through 60-140 m of sediments. Some intersect the seabed while others are buried and formed during earlier down-slope translation. Methane hydrates, the base of which is evidenced by aligned amplitude terminations or a bottom simulating reflection, form within the faulted succession.

We focus on a normal fault below the base of gas hydrates, which has a small downslope translation (~ 10 m offset) while its length (~ 21 km) shows that an extensive section of the margin has moved downslope. At the base of this fault, the free gas mainly accumulates on the updip eastern side of the normal fault. In the middle of the interval there are localized high amplitudes aligned along this fault. We also observed free gas sealed by hydrates at the shallower depth above this fault. So there is a close spatial relationship among the fault location, breached gas accumulation and the location of shallower free gas zone (FGZ), based on which a synoptic model is proposed. Gas hydrates formed in a faulted succession. As the base of gas hydrate stability zone (BHSZ) resets upwards due to sedimentation, the fault with higher permeability than surrounding sediments act as a conduit, channeling the released gas from hydrate dissociation upwards until it reaches the new position of the BHSZ. The free gas then can be stored in a FGZ or form new hydrates. Rather than migrate up the fault, the dissociated gas on the updip side of the fault would transport laterally in the same layer until it meets a seal. In summary there is a dynamic interplay among the hydrate dissociation, gas migration up along this pre-existing fault and gas re-sealing at higher levels below the hydrates.

The tear faults at shallower depth are also of high permeability and could be utilised as the gas migration pathways when the hydrate dissociation occurs there. Due to the common co-location of gravity faulting and hydrates in other continental and island slopes, this model should have general applicability and examination of other datasets may be productive.

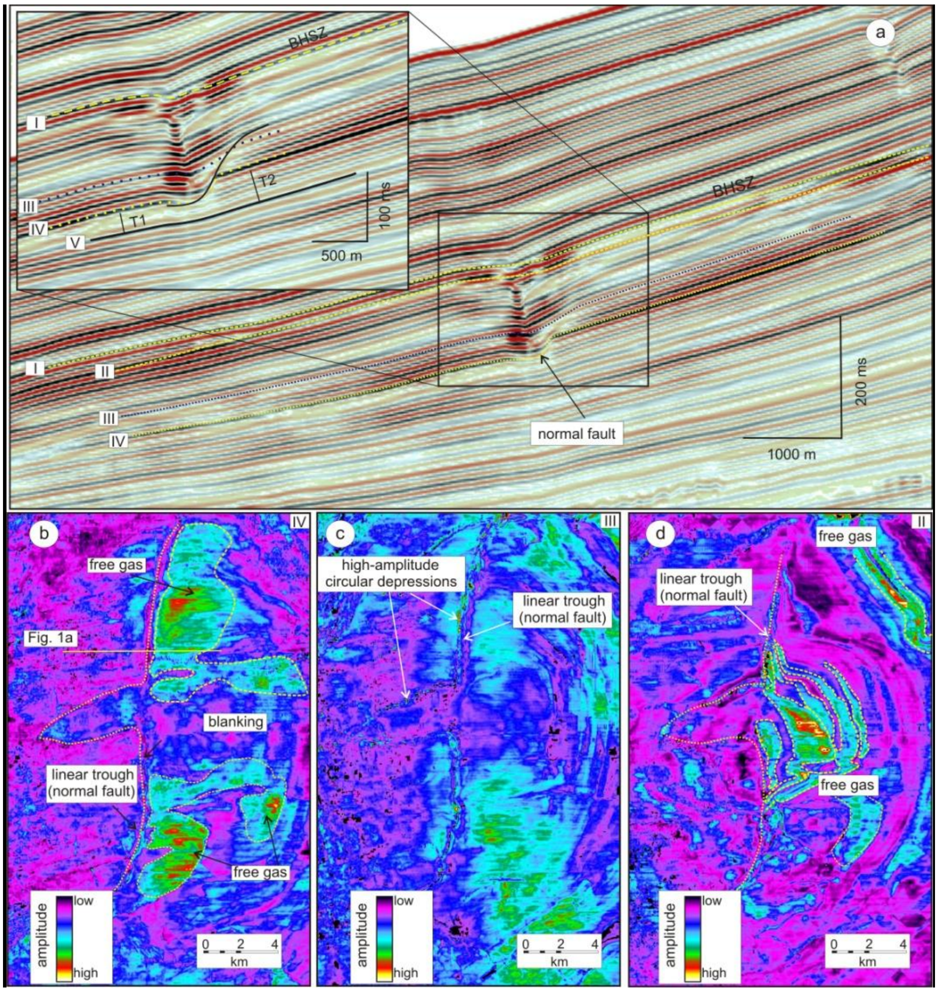


**Fig. 1.** (a): Representative seismic line, showing the normal fault, localized high amplitudes in the fault plane, BHSZ and FGZ. Inset: zoom in image of the black box, displaying the thickness change between the two sides of the normal faults. (b): amplitude map of reflections IV, showing the free gas accumulation on the updip eastern side of the normal fault. (c): Amplitude map of reflections III, showing the localized high amplitudes aligned along the fault. (d): RMS amplitude map produced within a window between the BHSZ and 50 ms bellow, showing the distribution of free gas zones.

## The Tectono-Stratigraphic Evolution of the Eastern Mediterranean and Implications for the Development of Petroleum Systems, Offshore Nile Delta and the Levant Margin

Abdulaziz Al-Balushi, Alastair J. Fraser , Chris A-L. Jackson, Philip A. Allen, *Department of Earth Science & Engineering, Imperial College London, Prince Consort Road, London, SW7 2BP, England, UK*

The Eastern Mediterranean basin has evolved through a complex tectonic history, which is thought to have started as early as the middle-to-Late Permian or as late as the Late Cretaceous. Previous studies have utilised mega regional plate tectonic reconstructions, combined with data from onshore geology in Cyprus, the Levant and northern Egypt, to investigate this complex tectonic history. More recently, 2D seismic reflection data, which has been collected by the oil industry, has provided new insights into the nature of the subsurface in the offshore region. In this study we use a large 2D seismic reflection and well data to test the existing models that have proposed for the tectonic history of the Eastern Mediterranean basin, and to develop a revised model that is consistent with our data.

Understanding the tectono-stratigraphic evolution of the Eastern Mediterranean basin is of particular interest to the petroleum industry due to a number of recent discoveries offshore Levant and Egypt. As a first priority, the nature and timing of Mesozoic rifting and opening of the Eastern Mediterranean has to be evaluated because it has a direct impact on the presence and maturity of Mesozoic source rocks and trap formation.

The initial phase of work included detailed mapping of faults and key stratigraphic surfaces, and delineation of the key structural and stratigraphic trends within the basin. Deep-seated, basement-involved faults have been picked and correlated with high confidence where data quality permits. However, in areas in which the deep structure is relatively poorly-imaged, shallower, post-rift structures have been used to interpret the deeper structure.

The resulting time-structure and isochron maps provide important constraints on the rifting direction and timing, and subsequent inversion in the Eastern Mediterranean. With respect to the rift-related extension direction, our mapping clearly indicates two major fault trends: NW-SE and NE-SW (Fig. 1). These faults border two main depocentres which are located in the northern Levant Basin and at the Nile Delta, and they are separated by the central Levant and Eratosthenes Seamount (ES). The age of rifting is relatively poorly-constrained due to the lack of deep well data with which to calibrate the age of the deeper stratigraphy observed on the seismic profiles. However, regional considerations, combined with subsidence modelling, suggest a Jurassic-Mid Cretaceous age for rifting, followed by continental break-up and post-rift thermal subsidence. The thermal subsidence phase was interrupted by compressive tectonics of the ‘Syrian Arc’ inversion episode, which was driven by Africa-Eurasia convergence. Our seismic interpretation indicates two main inversion episodes, which took place in Late Cretaceous and Late Mid Miocene times; both of these episodes formed important petroleum traps. Our early results favour a NW-SE directed opening of the Eastern Mediterranean (Fig. 2), which was initiated in the Early Jurassic.[2]

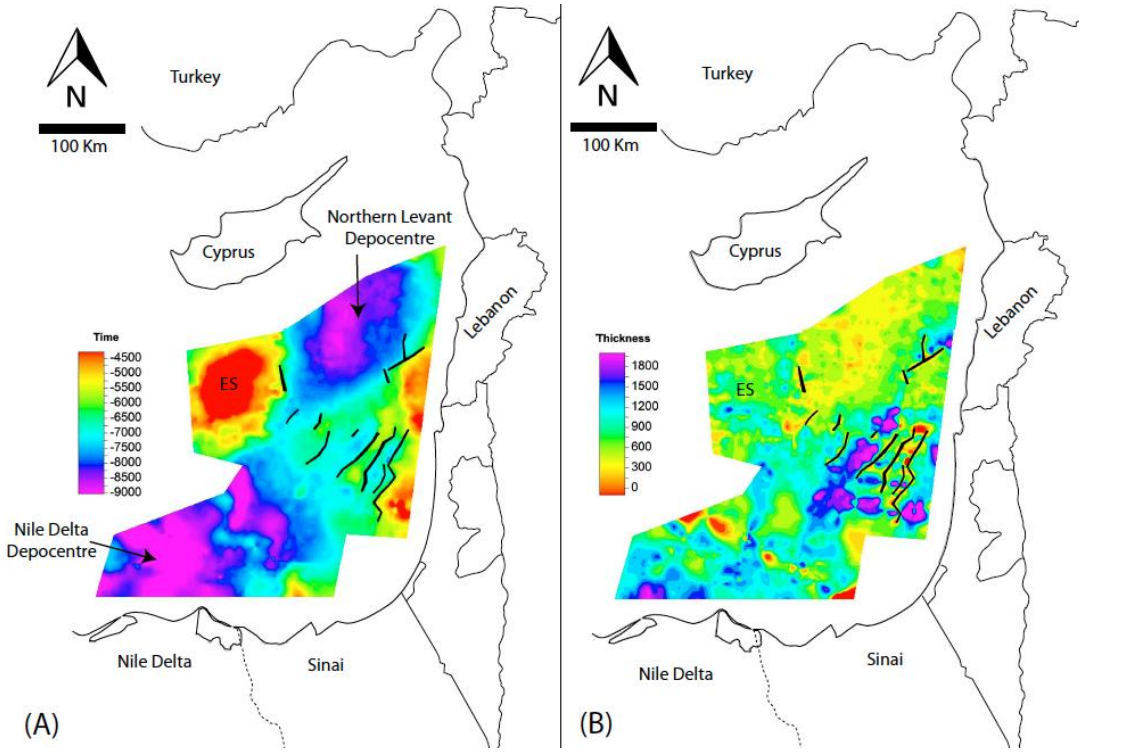


**Figure 1:** (A) Pre Jurassic time structure map and (B) Pre-Jurassic -Mid Jurassic isochron map.

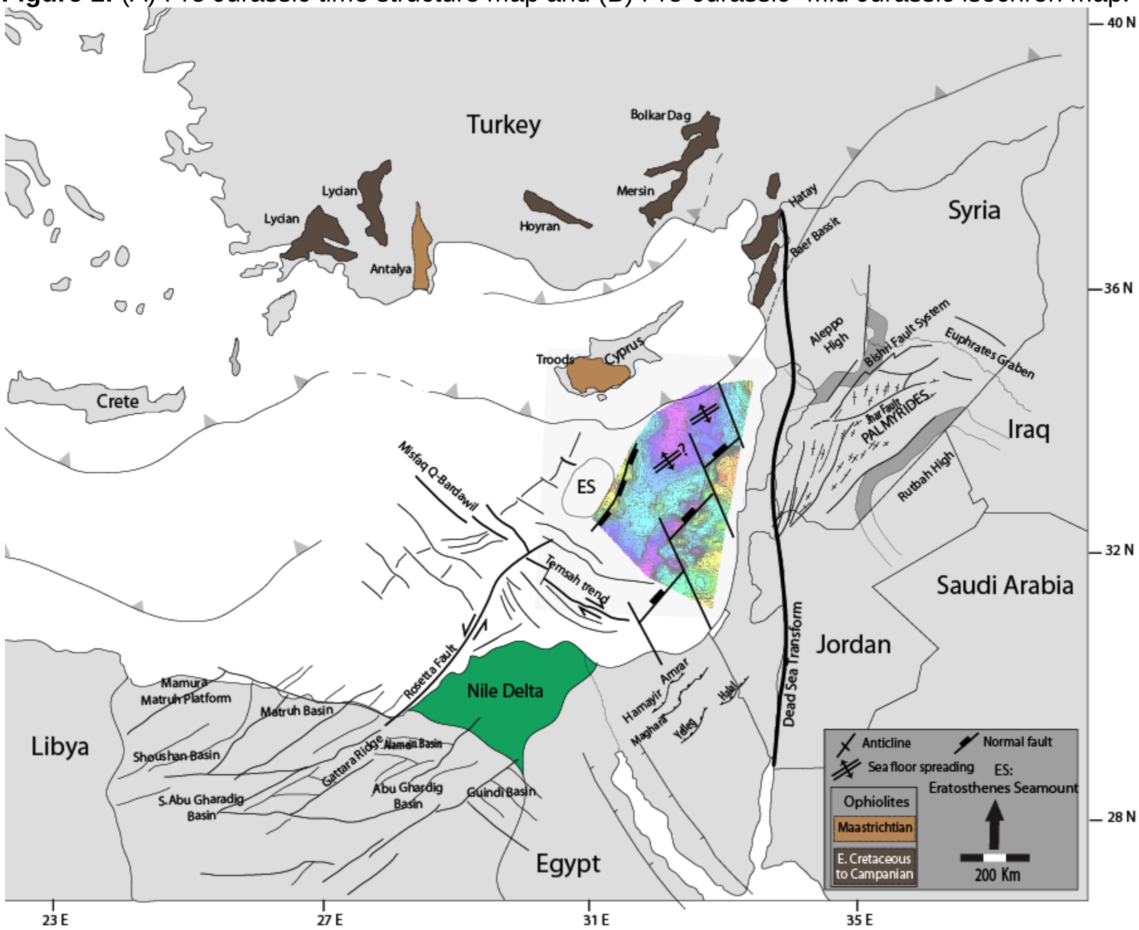


**Figure 2:** Regional tectonic map of the Eastern Mediterranean. Data compiled from: **1-** Abdel Aal et.al., (2000) – Offshore Nile **2-** Walley. C., (1998) - Palmyrides **3-** Moustafa. A., (2010) – Sinai penisula **4-** Wescott et al., (2011) – Western Desert **5-** Robertson.A ., (1998)-Ophiolites mapping **6-** Whitechurch.H et al.,(1984) Ophiolites' age.

## Structural Style of Fault-Propagation Folding in Salt-Influenced Rift Basins; the Stavanger Fault System, North Sea

Matthew M. Lewis[1], Christopher A-L. Jackson[1], Rob L. Gawthorpe[2]

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Fault-propagation folding is an important process during the early stages of fault growth; this is especially true in salt-influenced rift basins, where the presence of mechanically-weak, evaporite-rich units within the pre-rift succession may serve to decouple folded supra-salt strata from faulted sub-salt strata. Cover structures and their underlying fault blocks may be associated with hydrocarbon accumulations, although accurate identification of such structures can be difficult. In this study we aim to document the along-strike variability of and the controls on the structural styles that are associated with salt-influenced fault-propagation folds.

A 3600 km$^2$, high-quality, 3D seismic reflection survey has been used to document the structural style and evolution of the Stavanger Fault System (SFS), a 40 km long normal fault, located in the Egersund Basin, eastern North Sea. The SFS is a, sub-salt, basement-involved, NW-SE striking, SW-dipping normal fault, which has up to *c.* 1.5 km of displacement in the north of the study area. Displacement decreases progressively towards its tip in the south, and this decrease in displacement is expressed in the cover strata by the transition from a SW-dipping normal fault and half-graben in the north, to an un-breached, SW-dipping monocline in the south.

Five distinct supra-salt cover structures are recognised along the SFS and from north to south these comprise: (i) a NW-SE striking, basement-involved, breached monocline; (ii) a low-amplitude (*c.* 250 ms TWT), sub-circular, footwall diapir; (iii) a WNW-ESE striking footwall graben; (iv) a intensely-deformed, basinward-dipping monocline; and (v) a WNW-ESE striking, low-amplitude (*c.* 750 ms TWT), hangingwall salt wall. In addition to along-strike variations in total fault offset at basement level, we also document a southerly increase in salt thickness, and presence of marginal evaporates facies within the salt layer.

This study indicates a wide range of trapping types are associated with fault-propagation folds, and the style of coupling between sub- and supra-salt deformation in salt-influenced rift basins is dominantly controlled by the initial distribution of salt. In addition we demonstrate the kinematic-linkage between basement and cover structures, the processes of supra-salt strata fault growth, and its potential application to hydrocarbon industry.

## Characterising Permo-Carboniferous Glaciogenic Reservoirs on the Margin of the Lenard Shelf, Canning Basin, Western Australia

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Acquisition of a recent high quality 3D seismic survey (Bunda 2009) by Buru Energy Ltd. on the Lennard Shelf, northern margin of the Canning Basin, has allowed detailed analysis of the Permo-Carboniferous glaciogenic sediments. This provides insight into the stratigraphy and depositional architecture of the Grant Group, and valuable new data on the influence of tectonics and climate on the Late Palaeozoic ice sheet dynamics and distribution in the region. The seismic data covers an area of 223 square kilometres, and the study area contains 20 hydrocarbon exploration /appraisal wells that provide good well control for the lithofacies and mapped horizons.

The basal unit of the Grant Group (120-360 m thick) consists of mostly of sandstone with minor conglomerate and shale. This is deposited on a deeply incised unconformity. Below the unconformity, NW-SE to NE-SW oriented normal faults can be mapped, producing a series of half grabens, horsts and tilted fault blocks. These Carboniferous pre-Grant extensional faults show significant thickening of the Anderson Formation into the hanging wall, indicating syn-rift deposition. Activity of these faults cease at the Base Grant unconformity, prior to the deposition of Grant Group, therefore there was no direct syn-tectonic influence on its deposition. Although these pre-Grant faults were not active during Grant Group deposition, they have influenced the later glacial topography.

A series of valleys can be mapped, infilled by low amplitude discontinuous reflectors, interpreted to record a complex suite of glaciogenic facies. Discrete channels can be imaged, oriented NW-SE to N-S and ranging from 1500 to 3200 m wide and up to 240 m deep.

The middle unit (85-200 m thick) is characterised by continuous high amplitude reflectors. It is dominated by mudstones, comprising characteristic fining upward sequences. The formation generally thickens toward the southwest indicating an increase in accommodation toward the Fitzroy Trough. In addition, thickening is observed toward the southern margin, into a major underfilled glacial valley, which supports a local southward direction of ice movement.

The upper package (140-560 m thick) consists of massive and cross-bedded sandstones, and mudstones. Seismic facies vary from chaotic high amplitude reflectors to discontinuous low amplitude reflectors. Its maximum thickness is observed in a north-south trending valley that in places completely eroding the underlying section almost down to the basal Grant unconformity. RMS attribute extractions also show the presence of a network of anastomosing northwest-southeast oriented channels running oblique to the regional trend of the Fitzroy Trough. The morphology and size of this large valley system suggests glacial erosion, and this is interpreted to record the latest glacial advance, and a final glacial phase previously unrecorded in the basin.

The Grant Group is a proven hydrocarbon reservoir in the Canning Basin, however unlocking significant reserves has proved elusive. This study adds to our understanding of the depositional system and evolution of the basin, which will enhance future exploration.

## The Sedimentological Variability of a Potential Shale Source Reservoir: The Clare Shale Formation, West Ireland

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The success in recent decades of shale gas plays in the United States, such as the Eagle Ford, the Marcellus, and the Barnett shales has naturally led to interest in shale gas exploration in other areas. Attention is now being focussed on organic-rich shales in Europe in an effort to discover successful shale gas plays outside of the United States.

The Clare Shale Formation, west Ireland, is the lowest stratigraphical unit of a Namurian (Late Mississippian – Early Pennsylvanian) upward-coarsening basin fill succession.

The basin, known as the Carboniferous Shannon Basin, the Western Irish Namurian Basin, or the Clare Basin, has seen significant research activity since the 1950's, however in recent decades most of the research has been directed on the younger portion of the basin fill, such as the Ross Sandstone Formation and the Gull Island Formation. Work on the Clare Shale Formation in the past has focussed on establishing and refining a detailed biostratigraphical framework for the formation and the basin.

The Clare Shales are high in total organic carbon (TOC) with values up to 8.16 Wt % TOC recorded during fieldwork. The formation is also significantly thick in the axial region where 115 m and 74 m of the formation were logged.

Thermal maturities recorded in the past from the Clare Shales would suggest they are too overmature to have potential for shale gas. However, their high TOC's and significant thickness presents an opportunity to assess the variability of fine-grained successions that can be applied to similar mudstone formations with potential to be shale source reservoirs. The variability in sedimentology, microfacies, TOC, gamma ray spectrometry, and whole-rock geochemistry was studied from samples collected from three outcrop locations across the basin.

Understanding the variability inevitably aids our knowledge of the distribution of various shale source reservoir characteristics throughout the formation which can help in the evaluation of sweet spots and other factors which may affect development. This assessment of the variability within the formation also serves to expand the sedimentological knowledge of the basin down to the oldest stratigraphical unit.

## Helium – Exploration for an Elusive and Valuable Gas

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Helium is the second most common element in the universe but here on Earth reserves are dwindling at an alarming rate as demand threatens to exceed current sources. Indeed the reserves we do have owe their existence to serendipity, with their discovery being accidental rather than planned. Helium is classified a non-renewable resource since it cannot be recycled and any produced is ultimately lost to space. We currently lack knowledge on the processes of its generation, migration and eventual entrapment in the crust. The aim of this study is to understand these processes and hence develop an exploration strategy for potential gas fields.

The first helium field of note was discovered in Dexter, Kansas in 1905 and from that time onwards, the USA has been its prime exporter. There are currently 14 major helium fields which span 12 countries around the world including Algeria, Poland, Russia and Australia. Some of the larger fields are in the Hugoton-Panhandle area which spans the boundaries between Kansas and Texas, the LaBarge field in Wyoming and the Hassi R'Mel field in Algeria which is set to become the next largest exporter of helium and contains around 8400 million $m^3$ in reserves. With regards to industry and science, the largest single use of helium is in superconductors as a liquid coolant (28% of global demand). Currently, with the global helium shortage, helium prices are \$2.70/$m^3$ for crude helium and \$5.77/$m^3$ for Grade A helium. Helium is not only used in industry but also as a tracer for groundwater due to the easily discernible signal of its isotope ratios relative to atmospheric levels. This is useful for identifying the sources of the helium isotopes in the water.

Helium occurs as in two naturally occurring isotopes: primordial $^{3}$He from the formation of the Earth is degassed from the mantle whereas radiogenic $^{4}$He is generated via the radioactive decay of $^{238}$U and $^{232}$Th in the crust. Since U and Th increase in the upper crust due to the fractionation of the Earth, $^{4}$He is preferentially generated in the largest quantities in the shallow crust and is sometimes brought from depth by magmatism and advection of fluids. The generation of $^{4}$He has already been quantified as around $4.18 \times 10^{-10}$ atoms $m^{-2}$ $s^{-1}$ however there are several mechanisms suggested as to the degassing of $^{3}$He from the mantle which include escape by emplacement of small volumes of mantle melt which continuously degas. Migration has been thought of as two mechanisms: diffusion and then either transport in solution by groundwater, or as a component of other gases classified as superfluids such as $N_2$ and $CO_2$. Helium then migrates through faults and fractures in the rock until it is eventually trapped in a reservoir or reaches the surface and degasses to the atmosphere. Accumulation and eventual entrapment is currently thought to be a product of caprock properties, trap formation and trap destruction over time. By investigating these previously separate aspects of helium generation, migration and trapping we hope to be able to develop a robust strategy for helium exploration instead of one which relies on chance finds in wells already drilled to discover petroleum.

## Petrophysical and Petrological Properties of Hyaloclastite Deposits: Examples from the Hawaiian Scientific Drilling Project (HSDP) Phase II

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The Hawaiian Scientific Drilling Project (HSDP) Phase II was completed in 2001 and provided >3000m continuous log section through Mauna Loa, Hawaii (Fig. 1). The HSDP is a cooperative research project involving the University of Hawaai'i, University of California, Berkley and the California Institute of Technology. The main objectives of the HSDP are to investigate the causes of mantle plumes via drilling and geochemical sampling of a deep cored interval.

Core recovery from the HSDP was very high, providing an unparalleled data set of cored volcanic and volcaniclastic intervals. This contribution focuses on two sections at 1831-1870 and 2530-2597 m. These intervals were selected as they were originally classified as hyaloclastite, had very similar mean petrophysical responses and very similar geochemical affinities, and yet showed variation and variety in well log responses representative of sub 1.5 km burial.

Detailed logging and thin section analysis (optical, scanning electron microscope and EDX elemental analysis) was performed on each interval. Variations in well log response can be linked to changes in the interstitial or bulk mineralogy (dominant zeolite and phenocryst content) of the sample (Fig. 2). Unusually changes in well log response correlate to well to changes in grain size or clast density as observed in siliciclastic systems.

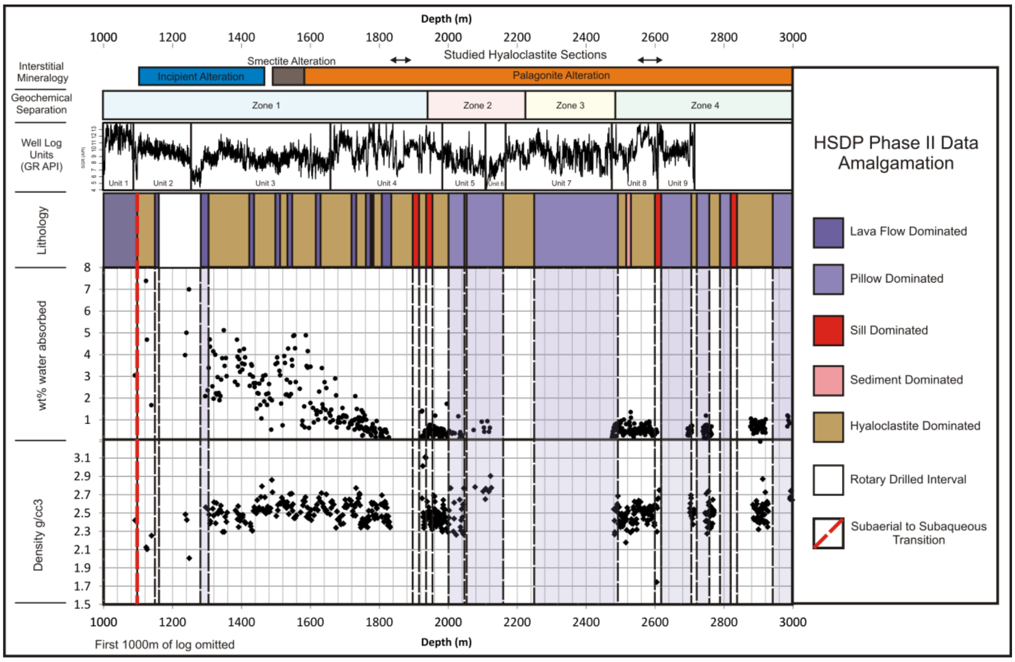


**Figure 1.** Combination of all HSDP phase II downhole data below 1000m. Core alteration from Walton and Schiffman 2003, Walton et al. 2004. Geochemical separation based upon Stopler et al.2004. Well log zonation based upon Buysch et a. 2000l and Peching et al. 2000. Lithology log provided by the ICDP. Density and water absorption data from Moore 2001 and Moore pers. comm.

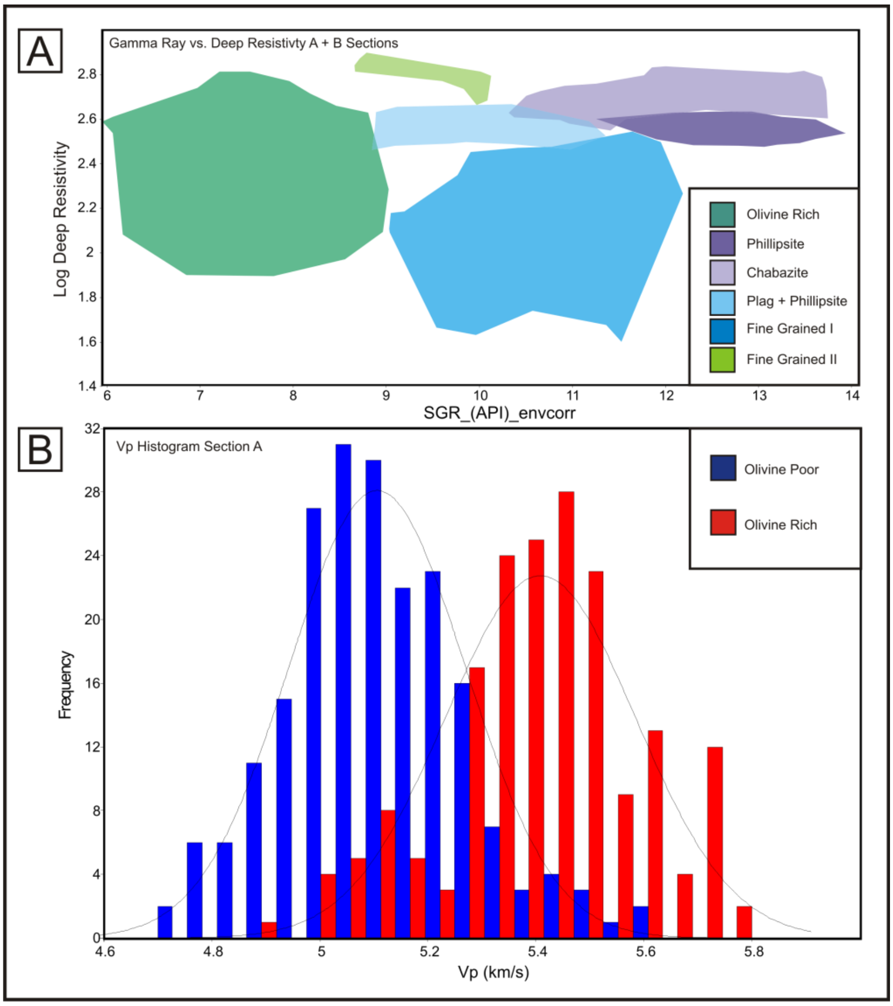


**Figure 2.** Gamma Ray vs. Deep Resistivity cross plot of both hyaloclastite intervals showing variation in phenocryst and interstitial mineralogy. A Velocity hA histogram can be produced from this data to show the variation in mean p-sonic values between olivine phenocryst rich and poor hyaloclastite intervals. A Kolmogorov-Smirnov test suggests the likelihood the data sets are the same is p = 1.275e-44. This very low probability suggests that the populations are unique. It is important to note that this is a worst case scenario as the olivine zone has thin interbeds which are olivine poor skewing the data to negative values.

## Forward Seismic Modelling of Shallow Marine Clinoforms Constrained by Outcrop Observations from the Cretaceous Western Interior Seaway, US: Analogues for the Krossfjord and Fensfjord Formations, Troll Field, Norwegian North Sea

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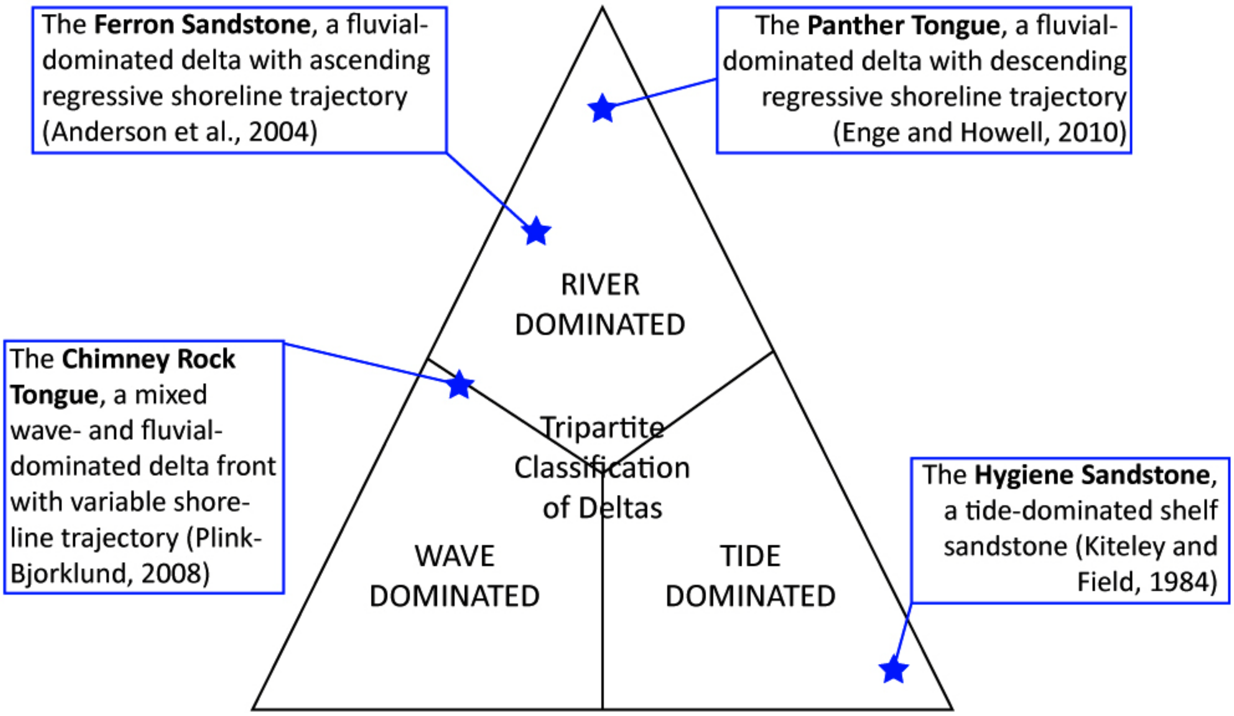
Seismic stratigraphy allows genetically related strata to be identified and mapped within a chronological framework. In this context, seismic reflection data can be used to undertake shoreline trajectory analysis, which defines gross stratigraphic architecture by tracking the position of shoreline clinoforms through time. However, the method is restricted by the resolution of the seismic data set. Furthermore, well-log data are typically widely-spaced in the subsurface and core recovery is limited, which limits the detail and confidence with which seismically imaged architectures can be interpreted. For example, well data may indicate many more lithological breaks in a clinoform set than are imaged in seismic data; this raises a number of important questions: (1) what combination of lithological attributes generates a seismic reflection?, (2) given the resolution issues that are inherent to reflection seismic data, how reliable are seismic images in understanding stratigraphic architecture?, and (3) how sensitive is the seismic response to subtle changes in the geometry and distribution of clinoform surfaces?

Forward seismic modelling is a novel method by which petrophysical properties are integrated with an interpreted lithology distribution to predict seismic amplitudes. Seismic modelling of outcrop analogues can therefore bridge the critical gap in both resolution and scale between well data and 3D seismic data. Stratigraphic architectures and lithology distributions observed in outcrop can be combined with subsurface petrophysical properties for different lithologies (e.g. from core measurements, density and velocity logs) to model their seismic response under reservoir conditions. This approach can constrain lithology distributions and reservoir architectures that would otherwise be overlooked or misinterpreted in the subsurface. The Krossfjord and Fensfjord formations are shallow marine sandstones that were deposited on the Horda Platform, eastern margin of the Viking Graben, northern North Sea during the Middle and Late Jurassic. They represent deposition in a series of deltaic, shoreline and shelf depositional environments sculpted by a mixed regime of wave, tide and river-mouth processes. Facies distributions and stratigraphic architectures of the formations are poorly understood as they have not been the focus of previous work, but the formations constitute a prospective reservoir interval in the area around the existing Troll, Brage and Gjøa fields. Seismic modelling of a range of outcrop analogues to the various shallow-marine depositional environments allows the sensitivity of modelled seismic response to different lithology distributions and stratigraphic architectures to be evaluated. A wide range of shallow-marine sandbodies containing clinoforms are exposed in outcrops of the US Cretaceous Western Interior in Utah, Colorado and Wyoming: (1) the Ferron Sandstone; (2) the Panther Tongue; (3) the Chimney Rock Tongue, and (4) the Hygiene Sandstone. The range of depositional environments represented by the chosen outcrop analogues reflects the uncertainty in the character of the subsurface sandstones and the sensitivity of the modelled seismic expression to various sedimentological and stratigraphic parameters, as outlined below.




For each analogue the geometry, distribution and lithological character of the clinoform-bearing units are quantified in order to create a range of detailed 'Earth models'. The data collected are matched to the observed facies changes in core data from the Troll Field, and petrophysical properties from those intervals are extracted. These data are then imported into the Earth model to create forward seismic models.

Analysis of forward seismic models of the selected outcrop analogues has allowed us to further quantify the seismic character of clinoform-bearing units in the subsurface at a range of scales. The technique outlined here, when integrated with core and wireline-log data, has enabled a more robust interpretation of subsurface stratigraphic architectures of the Krossfjord and Fensfjord formations. The results of the outcrop-analogue seismic models are also directly applicable to many other shallow marine reservoir sandstones, for which the outcrops described above are considered to be sedimentological analogues.

## Characterisation of Fracture Systems using Subsurface Digital Outcrop Models

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The characterisation of sub-seismic scale structure is a perennial problem within petroleum reservoir modelling. Mesoscale structures manifest at scales below conventional seismic thresholds impart significant anisotropy within the rock mass, resulting in permeability regimes several orders of magnitude greater or lower than those of enveloping matrix continuum. A common strategy to reduce reservoir uncertainty associated with such heterogeneity is to employ the use of analogues. And though outcrop analogues may provide lucid insights about the structural styles of their reservoir equivalents, conventional methods of fracture characterisation suffer manifest deficiencies, with direct sampling of the rock face biased and inefficient, and with lineament mapping from remotely sensed imagery resulting in poorly resolved datasets.

In the present work it is proposed that data capture and analysis techniques being developed within the burgeoning field of digital outcrop geology could provide a viable alternative to conventional means of fracture characterisation commonly applied to reservoir analogue studies. Here, a combination of terrestrial lidar and calibrated digital imagery is used to map exposures of the Triassic aged Helsby Sandstone Formation of the Cheshire Basin, UK, a salient analogue for reservoir objectives in the East Irish Sea Basin. Exposures of the Helsby Sandstone formation within the West Mine, Alderley Edge, Cheshire (**Fig 1**), form the principle targets for data capture. The use of subsurface exposures is motivated by the high degree 3D control afforded by the mine workings, aiding visualisation of the fracture network, whilst providing optimal conditions for the extraction of geometric fracture attributes.

A comprehensive areal survey was conducted over the West Mine triangular irregular network (TIN) models (**Fig 2:** A, B) with eigen-analysis based methods employed to aid the identification of fracture traces and facets, and with orientations constrained using a simple three point approach. Furthermore, a series of linear transect surveys across TINs of the West Mine exposures were used to determine fracture trace length and spacing. Fracture sets were delineated using a suite of qualitative and quantitative methods, with orientation statistics calculated for identified sets. Mean fracture spacing, trace length and density were then determined for individual sets, with appropriate censoring corrections applied.

To assess the validity of the approach, orientation statistics of identified sets were compared to an equivalent dataset collected via manual scanline surveys on surface exposures around the Alderley Edge locality. In similitude, lidar generated trace lengths, spacings and densities were compared to a commensurate dataset, acquired by manual scanlines referenced to virtual linear transect surveys within the West Mine. Finally, fracture statistics obtained for field and digital sets were used to construct representative discrete fracture network models which were upscaled to equivalent porous medium properties, enabling the differential in the modelled petrophysical attributes of the corresponding fracture arrays to be assessed.

Set distributions for virtually and manually derived networks show excellent agreement, with three closely matched orthogonal sets observed in both datasets. Moreover, in contrast to previous studies, fracture intensities are constrained by set, and thus constitute viable inputs for discrete fracture network modelling. However, the systematic underrepresentation of geometric fracture properties is observed within lidar datasets, attributable to censoring caused by the limited fidelity of imagery and model surfaces. The study results suggest that, whilst enhancing data acquisition rates and representation of the exposure surface, digital discontinuity analysis may introduce an additional suite of biases into fracture datasets.

**Fig 1:** Terrestrial lidar derived 3D model of faulted and fractured sandstones within the West Mine

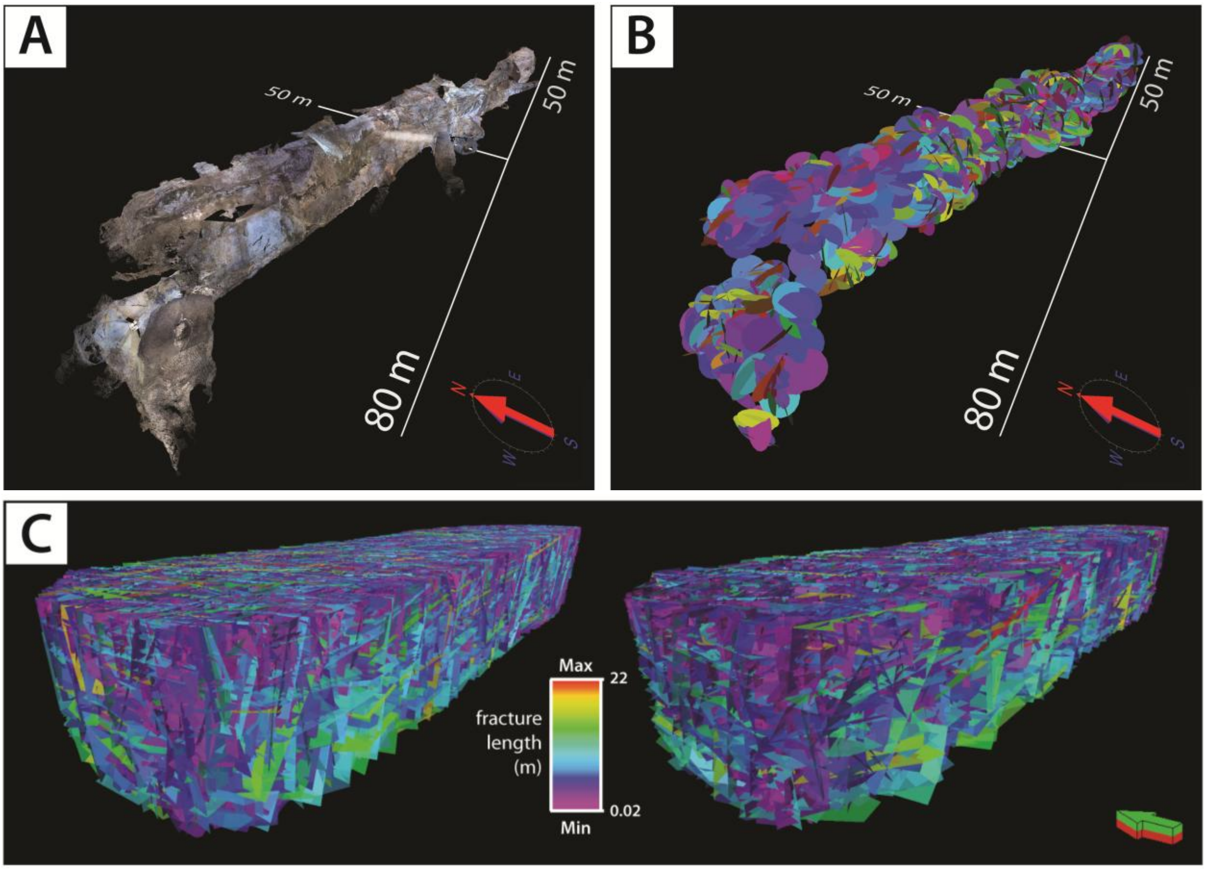


**Fig 2:** (A) Merged point cloud of the West Mine main chamber. (B) Individual fracture orientation measurements ($n$ = 1377) collected via digital fracture survey. (C) Discrete fracture network models using (*left*) manual and (*right*) lidar fracture data.

## Structural Modelling of a Fluvio-Lacustrine Analogue, Minas Sub-basin, Bay of Fundy, Nova Scotia, Canada

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The overall aim of this research is to understand and characterize fluvio-lacustrine deposits quantitatively in three-dimensions, and using the resulting geostatistical information to produce realistic geocellular reservoir analogue models. The well exposed outcrops of Late Triassic fluvio-lacustrine sandstones in the Fundy Rift Basin of Canada present exceptional analogues for hydrocarbon reservoirs in the North Sea and other similar systems, making them ideally suited to this project.

This study utilises a LIDAR-based digital outcrop mapping methods combined with traditional sedimentological logging and high resolution digital photography. Various software packages such as Riscan Pro, Petrel and Virtual Reality Geological Studio (VRGS), an in-house fit-for-purpose interpretation and modelling software were used in outcrop data acquisition, processing, interpretation and modelling.

Faults, fractures and changes in facies geometry and distribution are described in great detail. Fault characterization and modelling is a critical stage of the process as faults can either act as conduits or barriers to fluid flow. Few faults were observed especially of sub-seismic scale. Analysis of the master fault in the study reveals that the fault dips at $70^0$ and throws at about 23.203 m (figures 1 & 2).

Three-dimensional structural modelling is a powerful tool in earth sciences to examine petroleum and groundwater resources as well as suitability of subsurface reservoirs for nuclear waste disposal. Modelling of fluvio-lacustrine reservoirs can be very unreliable when only conditioned to seismic and well data as is the case in many sub-surface methods. By using outcrop analogue data to condition the geological model, uncertainty in the structural framework is reduced.


**Figure 1**. This figure shows fault interpretation. The fault dips at about $70^0$ with a thin clay smear, 5 cm on the fault plane. Notice the geometries of the beds and changes on the depositional environments on the hangingwall and footwall of the fault. Beds on the hangingwall show concave-upwards fold deposited in a lacustrine environment in contrast to the footwall.

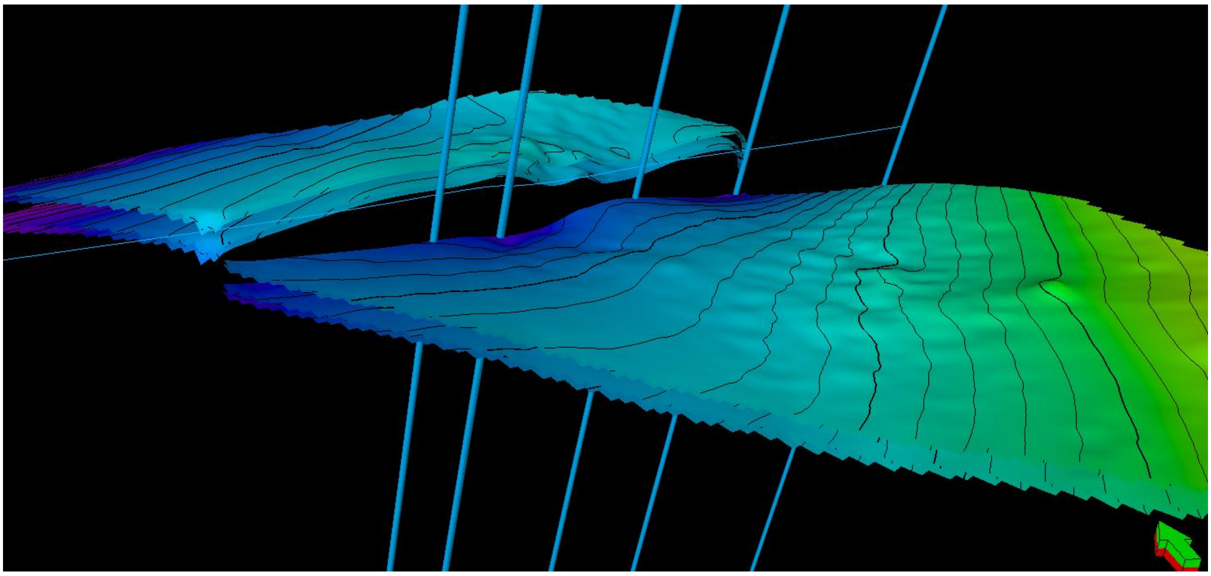

**Figure 2**. Fault and Horizon modelling in Petrel. The fault is the same as that in figure 1.

## NOTES

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