Palaeozoic Plays of Northwest Europe

26-27 May 2016

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Palaeozoic Plays of NW Europe

Geological Society of London, Petroleum Group
Burlington House, London. 26–27 May 2016

On behalf of the convenors, I would like to welcome you to this conference, which has been organised by the Petroleum Group of the Geological Society. In this booklet you will find the programme and abstracts for all of the talks given over the two days of the conference.

The last time a similar conference was held at the Geological Society was in January 1995. Since that time there have been new plays uncovered and many advances in our understanding of the various Palaeozoic petroleum systems in NW Europe. The Millennium and Southern Permian Basin Atlases were published in 2003 and 2010, and in 2014 a new project was set up in a collaboration between industry, the BGS and the UK government, to promote exploration of the Palaeozoic on the UKCS (part of the "21st Century Exploration Roadmap" initiative). In parallel with this, the Petroleum Group decided to host this conference in 2016, bringing together knowledge from both existing and new areas, including onshore as well as offshore plays, throughout NW Europe.

On behalf of the Petroleum Group Committee, I would like to thank and acknowledge my fellow convenors (below) for putting this conference together and for chairing the sessions; also to thank the staff at the Geological Society for their help and organisation, our conference sponsors and especially all those who have offered talks and posters. We hope that this will be a most interesting conference, and trust that you will find it both stimulating and enjoyable.

Hugh Dennis
Petroleum Group Convenor, Geological Society

Convenors and session Chairs

Henry Allen
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Origo Exploration
Paul Herrington & Nick Richardson
UK Oil & Gas Authority
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Reference :
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Thursday 26 May
Session One

Keynote Speaker: Revitalizing Exploration in Mature & Frontier Areas of the UKCS

Gunther Newcombe, *OGA*

Exploration and appraisal on the UK Continental Shelf is currently at an all-time low with 2015 seeing only 26 wells drilled with an even lower number in 2016.

There is a perception that the UKCS is “super mature” with very little remaining potential following the production of 43bnboe from the basin.

The reality is very much different with over 4bnboe discovered and waiting development and significant YTF numbers in both mature parts of the basin and frontier areas.

OGA is working very closely with the government and industry to unlock this future potential and maximize economic recovery for the UK

In 2015, and now in 2016, the government has set aside £40m to undertake frontier seismic acquisition and reprocessing and in addition support the industry and academia in developing a deeper understanding of the geology, play types and potential.

An example of this is the 21st Century Exploration Roadmap Project, which is collaboration between industry, BGS and the OGA, which has undertaken a regional evaluation of the petroleum potential that exists within the under-explored Palaeozoic plays of the UKCS.

At the end 1Q 2016 over 40,000 kms of new and reprocessed seismic data were made available to the industry free of charge to improve understanding of the Rockall Basin and the Mid North Sea High in preparation for the 29th Round Exploration Licencing Round. In addition to the release of data government funding has been made available to set up a competition to stimulate ideas and innovative approaches to interpret these data.

Tenders are currently being processed for new acquisition and reprocessing of the West of Britain and Orcadian basins and in addition a new regional study will be launched in 2Q 2016 which will include again evaluating the under-explored potential of the Palaeozoic

OGA is committed to revitalizing exploration in the UKCS and to be successful also needs the industry to display greater collaboration, and improved commercial behaviours to achieve success

NOTES

Keynote Speaker: Carboniferous Exploration in the Central and Southern North Sea: A 30 Year Personal Retrospective

Bernard Besly, *School of Geography, Geology and the Environment, Keele University*

The first significant discoveries of gas in Carboniferous reservoirs in the Southern North Sea were made in 1984, with the discovery of the Murdoch and Ketch Fields. Subsequent discoveries have been made over a wide area and a range of Carboniferous stratigraphy, but overall the Carboniferous has failed to live up to initial expectations, and dissemination of knowledge about the Carboniferous petroleum systems has been patchy and lacking in regional integration. This contrasts markedly with the rapid dissemination of knowledge and growth of understanding regarding, for instance, the Permian and Jurassic in the 30 years after initial discoveries in these systems in the 1960's and 70's.

In a review of the evolution of Carboniferous petroleum geology since 1984 a number of themes are identified that may help to understand its slow progress and provide pointers to future improvements in understanding. These include (in no particular order):

a) lack of recognition of the differences between the "Carboniferous play" and plays previously developed in the North Sea, particularly in respect of its complex stratigraphy and simplistic assumptions made about source rock and seal distribution;
b) the effects of the prolonged period of low oil price during which the first fields were developed;
c) changes in fashions and funding of academic research over the same period;
d) use of drilling and logging methodologies that, in retrospect, were inappropriate for Carboniferous successions;
e) a lack of basic analytical data in the public domain;
f) failures to carry out and publish basin analysis studies at scales appropriate for exploration evaluation;
g) inappropriate use of analogues;
h) lack of co-ordination across national boundaries

These themes are illustrated with examples from the UK onshore and offshore areas.

NOTES

The Search for a Carboniferous Petroleum System beneath the North Sea

R. Milton-Worssell, A. McGrandle, *OGA*

The search for a Carboniferous petroleum system beneath the Central North Sea, R. Milton-Worssell et al was published in 2010*, this pilot study showed how potential field data could be used to investigate deeper Palaeozoic basins within the Central North Sea. A follow-up study has been carried out which covers much larger area including the Inner Moray Firth, Witch Ground Graben, Mid North Sea High, the Central and Southern North Seas and parts of the onshore East Midlands. The study area also extends into parts of the Norwegian and Netherlands (Elbow Spit High) continental shelves. The advantages of this big picture approach with gravity and magnetic data is that it allows a broad regional view, with the advantage of more detail in the areas where high-resolution potential field data are present. It integrates interpretations of modern long-offset seismic datasets with potential field anomalies derived from dense grids of 2D and 3D gravity and magnetic data to present a regional-scale synthesis of Devonian, Carboniferous and Early Permian basin structures. The new long offset seismic data, with its deeper penetration, has proved to be of great use in calibrating the modelled basement surface. It reconfirms Lower Carboniferous basin development was strongly influenced by the disposition of granite-cored Lower Palaeozoic basement blocks of the Farne, Dogger, Devil's Hole Highs, and the Auk-Flora Ridge. Additionally they occur in blocks across the Mid North Sea High linking to the landward occurrences of these granite-cored Lower Palaeozoic basement blocks. The identification of Palaeozoic basins and structures in the North Sea provides a new target for future exploration in the mature North Sea.

NOTES

Keynote Speaker: Evidences for Palaeozoic Sourced Oils on the Norwegian Continental Shelf, With Links to Palaeozoic Bitumen & Source Rocks from Onshore Skandinavia & the Orkneys

Karlsen, D.A.,[1] Matapour, Z.,[1] Rønningen, A.,[1] Abay, T.,[1] Lerch, B.,[1] Flett Brown, J.[2] & Backer-Owe, K.[1]

[1]*Department of Geosciences, University of Oslo, N-0316 Oslo, Norway*
[2]*The Park Hillside Road, Stromness, Orkney, KW16 3AH, UK*

Recent advances in GC-MS technology and biomarkers concerning age specific Palaeozoic biomarkers has allowed a new evaluation of the source rock provenance of a migrated lacustrine bitumen (6609/11-1) of the Helgenland Basin, Offshore Norway. The bitumen which is waxy, isotopically light and with a very low V/Ni ratio is concluded to be of Palaeozoic age and of the same general family as the Beatrice oil, and with strong source rock facies-type-links to Devonian source rocks of the Orkneys.

Besides the implications to the understanding of the structural geology on the Norwegian Offshore Continental Shelf (NOCS), and the symmetry between the UK side and the NOCS side, this might suggest that there is good reason to believe that there exists on the Norwegian shelf Devonian basins which have been, or which might currently be “Petroleum Machineries” of the Beatrice type.

Oil from well 7120/2-1, close to the Gohta discovery on the Loppa High, is likewise concluded to be Palaeozoic, with the obvious implications this might have to exploration in the multi-source rock play of the Barents Sea, in which most traps to date have been found to contain oils from the Mesozoic sequences.

This study includes for comparison a series of Palaeozoic aged migrated bitumen samples from onshore Sweden, plus oils from the Central Graben, the Viking Graben, The Halten Terrace, and The Barents Sea, with the aim to shed light on the source rock age of migrated oils, from the Cambrian to the Cretaceous.

NOTES

Brittle Deformation History, Age and Attribute Analysis from the Devonian Orcadian Basin, Scotland: A Classic Fractured Reservoir Analogue Reassessed.

Holdsworth R.E.[1], Dichiarante A.M.[1], McCaffrey K.J.W.[1], Dempsey E.D[1], Selby D.[1], Conway A[2]. and Wilson R.[3]

Department of Earth Sciences, University of Durham, Science Labs, Durham, UK,
[2]ConocoPhillips (UK) Ltd,
[3]BP Sunbury.

The onshore Devonian sedimentary rocks of the Orcadian basin host significant localized zones of fracturing, faulting and some folding on all scales. New field and microstructural analyses carried out within the Devonian cover sequences in Scotland and Orkney reveal 3 main groups of structures based on orientation, kinematics and infill.

Group 1 faults trend N-S and NW-SE and display predominantly sinistral strike-slip to dip-slip extensional movements. They form the dominant structures in the eastern part of Caithness, and to a lesser extent on Orkney. Gouges/breccias associated with these faults display little or no mineralization or veining. It is suggested that these structures are related to Devonian ENE-WSW transtension associated with sinistral shear along the Great Glen Fault (GGF) during Orcadian and proto-West Orkney basin formation.

Group 2 structures are closely associated systems of metre- to kilometre-scale N-S trending folds and thrusts related to a highly heterogenous regional inversion event recognized locally throughout the field area, but especially on Orkney. Once again, fault rocks associated with these structures display little or no mineralization or veining. Group 2 features are likely related to late Carboniferous – early Permian E-W shortening associated with dextral reactivation of the GGF.

Group 3 structures are dextral oblique NE-SW trending faults and sinistral E-W trending faults with widespread syn-deformational carbonate mineralisation (± pyrite and bitumen) both along faults and in associated mineral veins. In a few localities (e.g. Brough, Scarfskerry, East Scapa faults) oblique reactivation of large pre-existing Group 1 faults has led to complex zones of localized transpression or transtensional folding, faulting and inversion synchronous with the carbonate and associated mineralisation events. Re-Os model ages of syn-deformational fault hosted pyrite in Caithness yield Permian ages (ca. 267Ma). This is consistent with the field observation that Group 3 deformation is synchronous with the emplacement of ENE-WSW-trending lamprophyres east of Thurso (ca 268-249 based on K-Ar dating). Stress inversion of fault slickenline data associated with mineralization suggest NW-SE regional rifting, an episode also recognized farther west in the Caledonian basement of Sutherland. Thus from St John's Point to Cape Wrath, Permian age brittle faults dominate the north coast of Scotland, forming part of a regional-scale North Coast Transfer Zone translating extension from the offshore West Orkney Basin westwards into the North Minch Basin.

We investigated fault size scaling in Caithness across 8 orders of magnitude using a combination of 1D and 2D methods. Fracture length was quantified from 10-4 to 104 m scales using remote sensing, outcrop and thin section datasets. The lengths are well described by a power-law distribution with an average exponent value of -1.039. Results are consistent with previous fracture analyses in similar lithologies from Norway (mesoscale) and offshore datasets in the North Sea (seismic/regional scale). Fracture aperture/width, constrained from 10-6 to 10-2 m scales, shows a similar -1 scaling exponent. Results from 2D box counting and

topology analysis on regional to mesoscales confirm self-similarity and reveal locally high fracture connectivity at fault intersections.

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The Palaeozoic Fractured Reservoir Play

Robert Trice, *Hurricane*

One of the potentially important Palaeozoic exploration plays of the NW European Continental shelf is naturally fractured reservoirs. The play type comprises a wide range of fractured reservoir types including Devonian-Carboniferous clastics (Buchan and Clair Fields), Silurian granite (Cairngorm discovery and Jens Sverdrup field), Zechstein carbonates (Argyll, Auk Carnoustie and Wissey fields) and carbonates of the Carboniferous.

Despite this potential there are relatively limited well penetrations or associated targeted data gathering of the Palaeozoic Fractured Reservoir Play and it is this status which has resulted in the play type remaining poorly understood. Given these constraints the presentation is intended to draw on UK and Global analogues to summarise, a) key production characteristics of fractured reservoirs and, b) exploration methods that have been successful in delineating fractured reservoir discoveries. The objective of presenting such analogue information is to highlight the production potential of the Palaeozoic Fractured Reservoir Play and suggest exploration strategies that may be pertinent for inclusion in a systematic evaluation of the North Sea Palaeozoic.

Structural Development of the Devono-Carboniferous Plays of the UK North Sea

Stavros Arsenikos[1], Martyn Quinn[1], Geoff Kimbell[2], Graham Leslie[1], Paul Williamson[2], Timothy Pharaoh[2], Alison Monaghan[1]

[1]*British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA.*
[2]*British Geological Survey, Nicker Hill, Keyworth, NG12 5GG.*

The Cenozoic- Mesozoic structure of the North Sea is well constrained by good quality seismic data and decades of exploration and production. However, the deeper basin architecture of the Palaeozoic play has been less well defined by seismic data, particularly on and around the Mid North Sea High. A study of the Devono-Carboniferous structure, stratigraphy and petroleum systems by the joint industry-government 21st Century Exploration Roadmap Project work is aimed at rejuvenating exploration from the Central North Sea/Mid North Sea High to the East Orkney Basin.

A regional structural overview of this part of the UKCS will be presented, incorporating interpretations from more than 2000 2D seismic profiles and 50 3D seismic volumes, plus a gravity, density and magnetic study. A complex picture of Devono-Carboniferous normal, strike-slip and reversed faults emerges on an inherited basement fabric, with numerous granite-cored blocks. Correlation with onshore UK and regional tectonics will be evaluated, together with the influence of syn- and post-depositional structural development on the Palaeozoic petroleum system.

Thursday 26 May
Session Two

Stratigraphy of the Devono-Carboniferous plays of the UK North Sea

T. Kearsey, K. Whitbread, R. Ellen, D. Millward, A. Monaghan, *British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA*

The Palaeozoic of the UK North Sea has been identified as a potential target for new exploration and production. The Devono-Carboniferous structure, stratigraphy and petroleum systems have been studied by the joint industry-government 21st Century Exploration Roadmap Project with the aim of rejuvenating exploration from the Central North Sea/Mid North Sea High to the East Orkney Basin.

Critical to this is a comprehensive understanding of the stratigraphy and facies architecture of the Devonian and Carboniferous. Over 130 of the wells with the longest Palaeozoic section have been re-interpreted, incorporating biostratigraphic information and seismic and gravity interpretations. Onshore lithostratigraphic correlations and field analogues have been integrated.

The facies architecture evolved through the Devonian and Carboniferous in response to tectonic events, sea-level change and sediment supply. Key findings include (i) the extent and inception of Lower Carboniferous delta systems and laterally equivalent basinal, mud-rich successions and (ii) the extent of Devonian source and reservoir rocks. An improved, chronostratigraphically-based understanding of stratigraphy and facies influencing the Palaeozoic petroleum system will be discussed.

NOTES

Hydrocarbon Potential of the Lower Carboniferous in the Dutch Northern Offshore

Marten ter Borgh, Bastiaan Jaarsma, Walter Eikelenboom and Eveline Rosendaal, *EBN B.V. Daalsesingel 1, 3511 SV Utrecht, the Netherlands.*

Following the play-opening success of the Breagh gas field we evaluated the potential of the Lower Carboniferous clastics petroleum play in the Dutch northern offshore. This evaluation incorporated seismic and well data from the Dutch, British and German North Sea sectors. A well analysis shows that the abundance and thickness of reservoir-quality sands increase from Breagh towards the northeast. Lower Carboniferous Scremerston coals are considered the most promising source rocks to charge these reservoirs in the Dutch A and B and the northern E and F blocks. The abundance of coal increases towards the north; from a few metres in well E02-02 to over 30 metres in A09-01 and over 20 metres in 39/07-1. Recently released 2D seismic data shows a high reflectivity sequence in the same area, possibly resulting from the presence of these coal layers. In the southern E and F blocks charge may occur from Lower Carboniferous basinal shales and laterally from Upper Carboniferous Westphalian coals. Basin modelling suggests that Palaeozoic source rocks generated gas in the Step Graben and Central Graben (A, B and F quadrants) during the Palaeogene and Neogene, following trap formation. Hydrocarbon shows and vitrinite reflectance data support this.

A regional post-well analysis shows that the play is virtually untested in the Dutch northern offshore. The wells date back to the 1970s to 1990s and only two out of thirteen wells had the Lower Carboniferous as their primary target. Two tests were positive but had high N_2 contents, one was negative, while ten wells were drilled off-structure and are therefore considered invalid tests of this play.

An initial screening shows that undrilled structures covered by Rotliegend Silverpit shales and Zechstein evaporites are present. In summary, the results show that the northern Dutch offshore has significant potential for renewed hydrocarbon exploration.

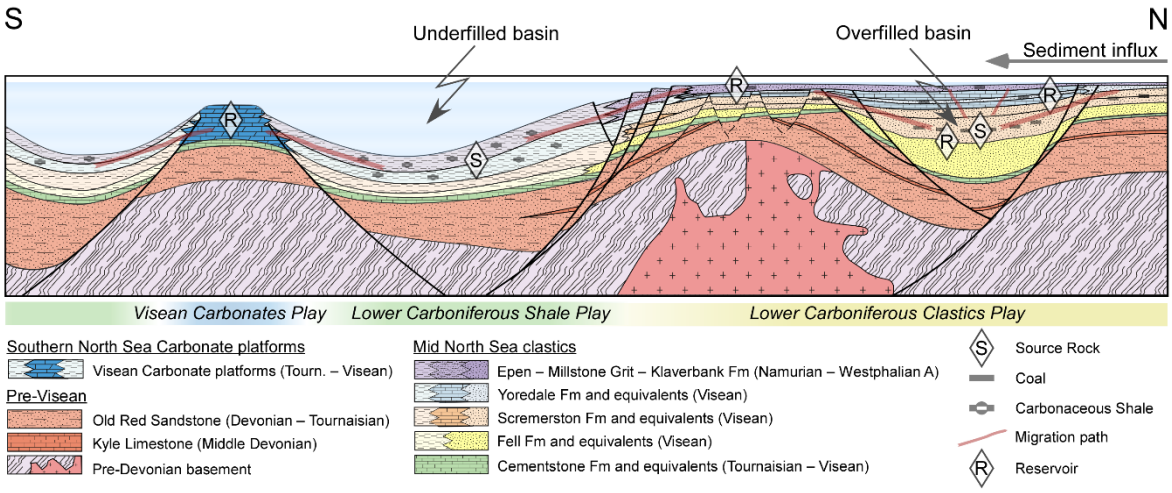

Figure: Overview of Lower Carboniferous petroleum plays in NW Europe. The Lower Carboniferous clastics play is present from the Mid North Sea area to the UK onshore. Further south, for instance in the Dutch onshore and the offshore P quadrant, Visean carbonate platforms are present.

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Unlocking the Resource Potential of the Bowland Basin

Huw Clarke, *Cuadrilla*

The Bowland Basin of NW England is a key part of the Pennine Carboniferous Petroleum System which is estimated by the British Geological Survey to hold over 1300 TCF of total original gas in place (TOGIP) of shale gas resource. The basin is a Lower Carboniferous (Dinantian) extensional basin which underwent at least two major phases of rifting and intrabasinal tectonics. The basin was inverted in late Carboniferous times and subsequent burial continued until mid or late Cretaceous time. The gas-bearing shale section is extremly thick (>6000 ft) intensly naturally fractured and relatively complex structurally. Ongoing geoscience studies are focussed on addressing the intrabasinal sedimentary architecture of the Bowland Basin, structural configuration, reservoir properties and the current stress regime. The Preese Hall-1 shale gas discovery well provides an opportunity to assess the shale gas characteristics of the Bowland Basin and its resource potential. Based on extensive core and log data the shale gas resource is estimated to be approximately 1 TCF per square mile (29 BCM per square kilometre). The gas is methane rich with little carbon dioxide and the less thermally mature parts of the succession includes significant wet gases. The gas density (gas per unit volume) in the Bowland Basin compares favourably with producing shales in North America, however, the gas saturated succession is significantly thicker.

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Carboniferous Shale Sedimentology in the UK

Sarah Davies, *Department of Geology, University of Leicester, University Road, Leicester, LE1 7RH, UK*

Fine-grained sedimentary rocks (mudstones, shales) have, until recently, been an overlooked part of the Carboniferous sedimentary record and yet may be key source rocks and potentially unconventional reservoirs. The sedimentological analysis of mudstones deposited in deep water basins, on shallow-water shelves and on floodplains during the Carboniferous, has revealed a variety of facies and shed new light on mechanisms for preserving organic matter of different types and abundances. Recent research analyzing a range of Carboniferous mudstones from UK basins suggests systematic variations in total organic carbon (TOC) content are related to the dominant delivery process (hemipelagic suspension settling vs sediment gravity flows). There is evidence that some muds deposited during significant marine transgressions may have been deposited as multiple event beds with reworking during widespread transgressions associated with glacioeustatic sea level changes. This is significant because the high sedimentation rates proposed provide a mechanism for the rapid burial and preservation of significant quantities of organic matter. There are also specific associations of thin-bedded carbonate-bearing mudstones, with high total organic carbon that were deposited during marine transgressions. Some of these organic-rich lithologies contain hydrogen-rich kerogen type II and have a significant potential for hydrocarbon generation. This process contrasts with previous interpretations of these intervals as exclusively suspension deposits formed during periods of slow sedimentation. A comprehensive analysis of the δ13C composition of sedimentary organic matter indicates that the source and delivery mechanism of the sediment contributes to the type of organic matter preserved at an individual location. This research revaluates Carboniferous successions, and long-held views on sedimentary processes, the use of geochemical proxies and the implications for organic carbon preservation.

NOTES

Palaeozoic Sequences of the Midlands Microcraton

Malcolm Butler[1] and Rachel Jamieson[2]

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[2]*Shell Centre for Exploration Geoscience, Heriot Watt University, Riccarton, Edinburgh EH14 4AS*

The British Isles has experienced a long and complex tectonic evolution, which can be partially elucidated from mapping of its spectacular onshore exposures. However, in many areas subsurface data is required to fully realise the geometries, particularly as we move into older stratigraphy. Previously such subsurface data was available through the UK Onshore Geophysical Library (UKOGL) in the form of seismic profiles and borehole data. However, single 2D seismic lines only provide a snapshot of the geology and recently the authors have been involved in the construction and interpretation of composite profiles for UKOGL that aim to provide a more regional perspective on the subsurface geology and evolution of the British landmass.

This paper aims to use these regional seismic data to describe the Palaeozoic sequences across the Midlands Microcraton ("MMC"), which are often well-imaged and regionally provide insight into the deformation history of a region in which outcrops of pre-Mesozoic rocks are sparse. The north-eastern boundary of the MMC is defined by the Anglo-Brabant Deformation Belt, which runs from Kent through to the eastern side of the Derbyshire Dome, and the western boundary is defined by the margin of the Welsh Basin, which coincides with the edge of availability of seismic reflection lines. Distribution of seismically-reflective Lower Palaeozoic rocks in the area is affected strongly by Acadian deformation and erosion, although it has historically been difficult to distinguish between Acadian erosion and that associated with later Variscan compressional and uplift events. The results of the regional study provide a better insight into the differentiation of the two erosion events while providing a more detailed description of the geometries seen in and around the MMC.

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Palaeozoic Gas Potential in the Weald Basin Of Southern England

Christopher Pullan and Malcolm Butler, *UK Onshore Geophysical Library, 93-99 Upper Richmond Road, Putney, London SW15 2TG*

Gas has been found in a several locations in the Weald Basin, particularly along the northern margin. The majority of the gas is dry, with high methane content and often associated nitrogen. Isotopic evidence indicates that the gas is from a thermogenically mature marine source. Although there is evidence of some shallow, biogenic gas in the Weald Basin, only the lowermost part of the Liassic is projected to have reached the thermogenic gas window before Tertiary uplift. Estimated maturities from isotopic data from the main gas accumulations indicate significantly greater levels than those projected for Liassic shales: thus, the gas is thought to have originated from Palaeozoic rocks.

Knowledge of the distribution of Palaeozoic rocks subcropping the Variscan Unconformity in this area is restricted by limited seismic penetration and well control. However, available information suggests that their distribution owes more to Acadian erosion than Variscan. It is thought that the Upper Devonian and Lower Carboniferous transgressed over a thick Tremadocian shale sequence in the western Weald and over folded Silurian and Lower/Middle Devonian rocks in the central Weald. In the east, the metamorphosed Lower Palaeozoic rocks of the Acadian-age Anglo-Brabant Deformation Belt underlie the Upper Devonian and Lower Carboniferous in the Kent coalfield. There is some evidence for the presence of isolated basins of late Carboniferous or early Permian clastics in the central Weald but no significant coals have been encountered to date. Regional studies suggest that the only suitable Palaeozoic marine source rocks encountered in drilling to date are post-Acadian aged Devonian shales. Maturity analysis indicates that these are not overmature but have reached the gas window.

These indications of a deeper gas source open up the opportunity for plays beneath the traditional Jurassic reservoirs of the Weald Basin, with hydrocarbons trapped in Palaeozoic and Triassic reservoirs.

NOTES

Silurian Shale Gas of Poland: Integrating Geochemistry, Palynology, Lithofacies for Source Rock and Reservoir Quality Interpretation

Martine Hardy, Jon Kaufman, Cara Davis, Kevin Bohacs, Pawel Lis, Stewart Molyneux

For the past 6 years, Poland has experienced exploration activity associated with an emerging shale gas/liquid play in Upper Ordovician to Lower Silurian mudstones. The prospective section is part of the southwestern margin of Baltica. ExxonMobil had acquired a large acreage position to test the potential of the play. As part of this evaluation, reservoir and source studies were performed on samples from an extensive collection of conventional core archived in Poland.

Lithofacies were described in detail from cores and eighty samples selected for palynology, organic geochemistry and GRI porosity / permeability analyses. A subset of samples were selected for advanced biomarkers characterization and nanometre-scale pore imaging using SEM on BIB- (Broad Ion Beam milling) prepared samples.

Though shale matrix porosity and permeability have not been directly linked to source facies or level of thermal maturation, SEM imaging revealed nanometer-scale pore architecture development only in selected organic matter types.

Integrating palynological and organic geochemistry results allowed classification of the source rocks as restricted inner ramp (excellent oil-prone), mid ramp (good gas-prone and poor oil-prone), and outer ramp (poor gas-prone). Moreover, organic preservation is inversely proportional to intensity of bioturbation, confirming that bioturbation is a key control on source quality and potential. Despite the paucity of land plants in the Early Silurian, marine source rocks have the potential of being both oil-prone, as expected for such rocks, and gas-prone during primary generation. Areal and stratigraphic variations in source rock quality, coupled with thermal maturity, exert major controls over reservoir quality and commodity types in the play.

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Friday 27 May
Session Three

Keynote Speaker: The Structural Stratigraphic Development and Petroleum Habitat of the Loppa High in the Barents Sea

Hans Rønnevik and Harald Brunstad*, Lundin Norway*

The Loppa High is established as a prolific province with several proven and potential play types related to reservoirs in Perm- Carboniferous, Triassic, Jurassic, Cretaceous and Tertiary with source rocks in Upper Permian, Triassic and Upper Jurassic. Resulting discoveries are Skalle, Salinas, the Johan Castberg discoveries, Gohta and Alta. The basic concepts were identified in the 1970's and unsuccessfully explored in the 1980's. The area was considered to have flushed oil reservoirs due to leakage to surface related to erosion and glacial overburden. Such a hypothesis had factual and conceptual weaknesses and several companies entered into an active exploration campaign in the area from 2007 and onward. Discovery breakthroughs are the result of exploration based on 3D seismic and a belief in late and ongoing oil migration that compensate for leakage.

The Loppa High is at Base Cretaceous level bounded towards the Bjørnøya Basin in the north by a NE-SW Late Cimmerian wrench zones and towards the south by the Hammerfest Basin by a NW-SE wrench zone. The west flank is defined by Upper Jurassic rotated fault blocks. The high was eroded and Lower Cretaceous and Paleocene fan systems deposited. The Jurassic fault blocks and fan systems have resulted in several discoveries.

The Palaeozoic inner core of the Loppa High consists of a Base Triassic high bounded by the Polheim Platform in the west. The Loppa High was part of the west flank of large Permo-Carboniferous Barents Sea basin with deposition of carbonate buildups and shale and evaporates. The basin linked up with Greenland in the west. In Late Permian and early Triassic the are was inverted and acted as local provenances for clastic flank deposition. The uplift was essential for the development of karstification and clastic reworking that are essential for the Late Palaeozoic and early Triassic plays. The area subsided during Triassic and thick Middle to Upper Triassic deltaic deposition prograded from east and south.

NOTES

The Alta Discovery: Chasing the Palaeozoic Play on the Loppa High after the Gohta Discovery

Harald Brunstad[1], Terje Hellem[2], Trond Kristensen[1] and Torodd Nordlie[3]

[1]*Lundin Norway AS*
[2]*Idemitsu Petroleum Norge*
[3]*Dea Norge AS*

The drilling of the Alta multiple target prospect on the southern Loppa High was planned before the 7120/1-3 Gohta discovery in 2014, identifying Palaeozoic as one of several targets in the well. However, with the Gohta discovery the chance of discovering hydrocarbons in the Upper Palaeozoic carbonates was upgraded for the Alta Prospect. Like Gohta, the Alta prospect sits updip of a previously drilled well on the same structure (7120/2-1, 1985). That first well had found excellent hydrocarbon shows in karstified carbonate reservoirs in the Ørn Fm, which are stratigraphically older than the karstified cherty limestones of the Røye Fm in the Gohta discovery. Pressures throughout the carbonates (apart from the uppermost metres) established a water gradient and four DST's all confirmed water flow. However, the uppermost DST also produced 1-2% oil, and Lundin partners Idemitsu and Dea identified the possibility that this oil was produced from an oil zone above the interval covered by pressure points.

The Alta prospect was drilled by well 7220/11-1 in 2014. The shallower Triassic targets were found water wet, but the deeper carbonates contained a gas cap above an oil leg – with an oil-water contact at a depth similar to the uppermost part of the DST-interval of the old well that flowed some oil with the produced water. The discovered volumes in the recent Alta and Gohta discoveries in the same neighborhood move the area closer to commerciality. However, carbonate reservoirs are complicated when it comes to reservoir properties and their spacial distribution and dimension. Accordingly there is a need for extensive geological, geophysical and reservoir studies and more delineation wells to mature the understanding of the structure and the area.

Acknowledgements to collegues in Lundin Norway AS, Idemitsu Petroleum Norge, and Dea Norge AS.

NOTES

Keynote Speaker: Back For More? The First Permian Oil Discovery in the Barents Sea Has Many Analogues in the Sverdrup Basin, Arctic Canada

Benoit Beauchamp, *Department of Geoscience, University of Calgary, Canada*

The 2013 Gohta oil discovery is the first significant discovery in the Permian succession of the Barents Sea. The oil pool lies beneath a sub-Early Triassic angular unconformity, suggesting block faulting and tilting prior to the onset of Triassic sedimentation. The reservoir rocks are Permian spiculitic cherts and heterozoan carbonates of shallow origin that accumulated at a time of cool oceanographic conditions. The porosity may be the result of extensive sub-Triassic subaerial karsting. The seemingly unique set of attributes of the the Gohta Discovery has been observed at a number of localities in the Canadian Arctic Archipelago. The Sverdrup Basin was adjacent to the Barents Sea area throughout its Late Palaeozoic-Mesozoic history prior to the break-up of Pangea. The succession is thicker than that of the Barents Sea, owing to greater subsidence rates, but its stratigraphic sequences are identical. Permian spiculitic chert is widespread, especially in the Late Permian succession, when carbonates were all but eradicated. The loss of carbonates can be in part associated with cooler oceanic conditions and possibly to upwelling-enhanced ocean acidification along NW Pangea. Late Permian organic-rich shales locally interfinger with the chert and may constitute a source rock. Porosity is unusually high in Late Permian chert. Large carbon isotopic depletion in carbonate material beneath the sub-Triassic unconformity suggests extensive meteoric leaching occurred. The sub-Triassic unconformity is widespread and one of the most significant in terms of base level drops in the history of the basin. The unconformity is also locally angular and associated with basal conglomerates of Permian pebble to cobble spiculitic chert clasts. An angular relationship is observed on northern Ellesmere and Axel Heiberg islands. From these observations we conclude the set of conditions that led to Gohta is a genuine play worth exploring.

NOTES

The Breagh Field

Richard Symonds, *DEA UK*

The Breagh Field is the first UK offshore field to produce from the Lower Carboniferous Yoredale Group.

Production started in November 2013 from four wells. Four more wells were brought on stream over the following twelve months at which point peak production of 150 mmscf/d was reached. The field has been developed using an unmanned platform, linked by a dedicated pipeline to processing facilities at Teesside where the control room is situated.

The field covers an area of about 10km by 10 km and was developed on the basis of seismic originally acquired in 1996 and a relatively small number of closely-spaced appraisal wells.

Development well results have suggested that the structure is more planar than it appeared in either time and depth-migrated seismic data. Recent depth conversion routines applied to non-proprietary data shot in 2014 have sought replicate this. Well results revealed a 1000ft stratigraphic interval to be present subcropping within the closure, twice the interval known at the point of field sanction. Large variation in initial well rates from different parts of the stratigraphy led to a modification of well design to fracked completions for wells 7 and 8.

The current focus is on de-risking further development activity to ensure it is profitable even in a low gas price scenario.

NOTES

Role of Tectonic Inversion in the Structural Evolution and Petroleum Prospectivity along the Northern Margin of the Southern Permian Basin.

Rachel Jamieson & John R. Underhill, *Centre for Exploration Geoscience, School of Energy, Geoscience, Infrastructure & Society, Heriot-Watt University, Riccarton Campus, Edinburgh, EH14 4AS, UK*

The Southern Permian Basin is a major, Late Permian-age, W-E striking intra-continental basin that stretches from the east coast of the UK, across the Southern North Sea to onshore Poland. It is defined to the north by the Mid North Sea High (MNSH), which separates it from its North Permian Basin counterpart, and the Anglo-Brabant Massif to the south. The basin hosts a major petroleum province in which gas, sourced from the underlying Upper Carboniferous, resides in Carboniferous, Permian and Triassic clastic reservoirs.

The most significant reserves occur on the southern side of the basin, where prospectivity is dominated by structural traps largely created during post-depositional structural inversion of normal fault precursors. The traps contain aeolian and fluvial sandstones belonging to the Permian Leman Sandstone Formation (LSF). The LSF reservoir was classically though to shale out to the north into an area termed the Silverpit Basin where it was replaced by the Silverpit Claystone Formation. Disappointing early exploration results on the northern margin of the Silverpit Basin at Rotliegend level and limited successes in the underlying Carboniferous instead, led to the perception that the area was devoid of the LSF reservoir fairway and discouraged further exploration along the southern side of the MNSH. It was only after successful drilling in 2008 of the large Cygnus structure which was found to contain gas in both Carboniferous and LSF reservoirs, that exploration interest was reignited in the area.

The aim of this paper is to outline how a new understanding of the tectonic evolution in the Cygnus area contributes to the description of a hitherto neglected LSF play fairway in the Southern North Sea Basin. We focus in particular on the role that reactivation of precursor normal faults against the MNSH had in not only controlling reservoir thickness and distribution but also the internal compartmentalisation of the field. Integration of the structure and sedimentology suggest that the play fairway is likely to extend along strike and that further prospectivity exists in both UK and Dutch offshore waters.

NOTES

Structural Elements of the Northern Silverpit Basin – Implications for Hydrocarbon Prospectivity

Matthew Dack and Gregor Duval, *CGG*

The UK Northern Silverpit Basin is part of the wider Southern North Sea gas basin. To date around 85% of gas production in the region has been from the Palaeozoic Rotliegend play, with recent exploration successes including the Cygnus discovery in Quadrant 44. The Silverpit Basin has undergone a complex tectono-stratigraphic history of continental collision and rifting with associated fault activation and reactivation. Using CGG's Lodestone 3D seismic survey and Insight Earth™ software, a structural analysis of the Northern Silverpit Basin has been conducted. Using Automated Fault Extraction (AFE) three distinct fault trends have been identified. The first and most dominant in the region is a NW-SE orientated trend, inherited during the Caledonian Orogeny and the closure of the Tornquist Sea. This collisional event created underlying basement structural lineaments that have been reactivated through geological time. Due to the oblique orientation of later stress regimes to this basement structural grain, later fault reactivation has been created predominantly by a process of oblique-slip. This has led to the creation of additional NE-SW and N-S fault orientations in the Late Palaeozoic, Mesozoic and Cenozoic as a result of the Variscan and Alpine Orogenies respectively. These fault trends have played a fundamental role in the petroleum system of the region. Palaeozoic faulting has primarily prevented up-dip migration of gas away from the region. Fault reactivation during these orogenic events has created numerous dip closures in the Carboniferous and Permian that form main exploration targets. In addition, faulting has allowed for primary migration of Carboniferous gas into shallower reservoirs, whilst later fault reactivation and Rotliegend structuration may have resulted in re-migration of gas into the faulted closures of present day discoveries. Finally, understanding the dominant stresses involved in fault reactivation is crucial for assessing lateral seal properties and reservoir compartmentalisation.

Figure 1: Automatic Fault Extraction Over the Cygnus Field using CGG's Insight Earth Software

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Assessing the Petroleum Potential of Devonian Carbonates in the Mid North Sea Area

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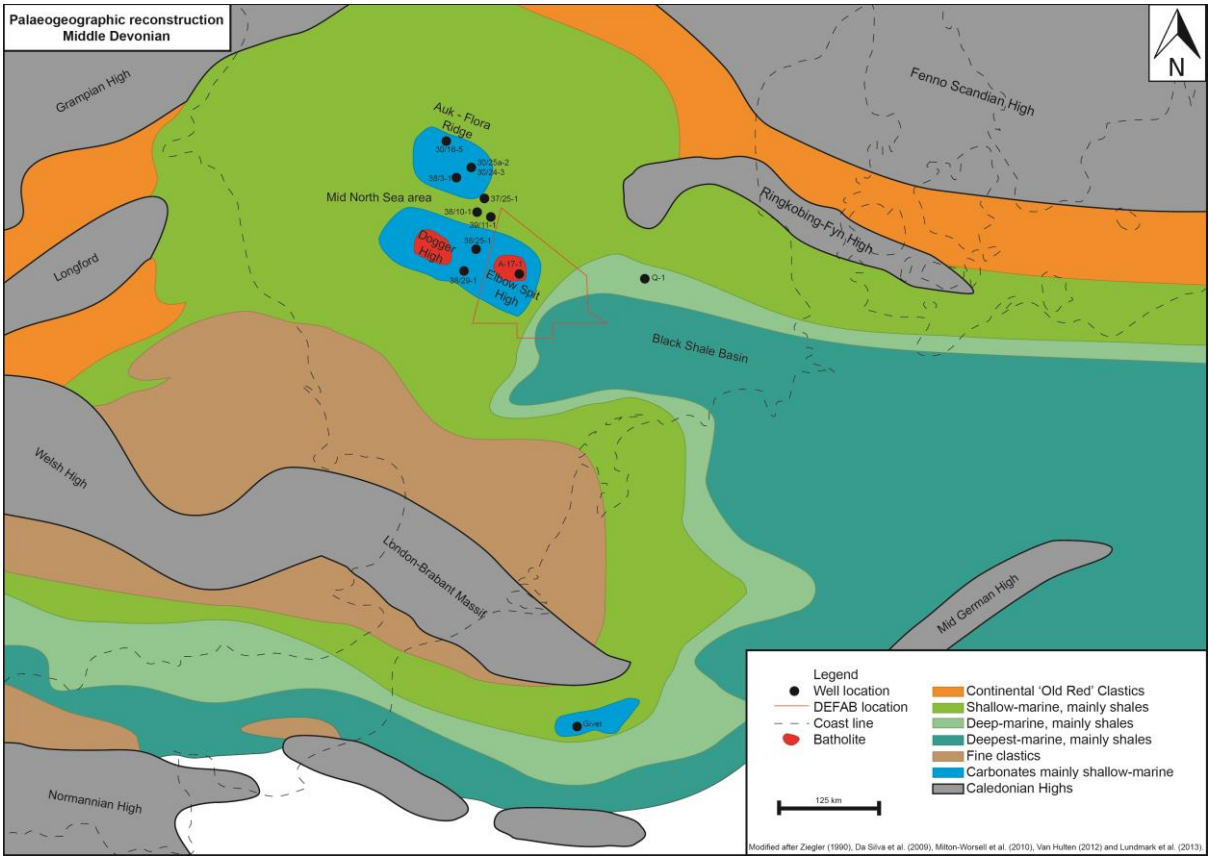
The development and distribution of Middle to Upper Devonian carbonates in Northwest Europe has always been rather uncertain due to a lack of well data and seismic coverage. Recent 3D and 2D seismic data was used to better constrain the regional distribution and character of these carbonates and to assess its petroleum potential in the northern Dutch offshore.

In this study area, a cyclic laterally continuous seismic package has been interpreted as the Middle Devonian Kyle Limestone, in between Lower and Upper Old Red clastics. The few wells that penetrated this formation have been compared with outcrops in Belgium. Large scale palaeogeographic reconstructions were used to predict Devonian ocean circulation in the region. This helped in understanding nutrient flows and growth rates of platforms, and in comparing the system with time-equivalent and oil-producing carbonate systems in the Western Canada Basin. Synthetic seismic profiles were modelled using platform geometries from outcrops in Belgium and rock properties from Canadian wells. These profiles were compared to the geometries observed on seismic.

Integration of the results indicates that shallow-marine carbonates developed in an extensive ramp or rimmed platform setting. The best reservoir and source rock potential are expected at the edges of the carbonate system, an area where no wells have been drilled to date. Seismic attribute analysis shows that acoustic anomalies are present that line up with a regional fault trend. It is proposed that these anomalies result from hydrothermal dolomitization resulting from fluid flow along the faults, enhancing reservoir quality.

From the similarities between the system in the study area and producing time-equivalent carbonates it is inferred that the Devonian carbonates in the Mid North Sea area have petroleum potential that justifies further exploration.

Figure: Middle Devonian facies distribution, modified after Ziegler (1990), Da Silva et al. (2009), Milton-Worsell et al. (2010), Van Hulten (2012) and Lundmark et al. (2013).



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Friday 27 May
Session Four

Assessment of the Presence of a Devonian Play on the Northern Margin of the Mid-North Sea High and Southern Central Graben - Implications for Hydrocarbon Prospectivity

Mercedes McKay[1] *&* Matthew Dack[2]

[1]*RHUL*
[2]*CGG*

With projects such as the industry 21st Century Exploration Road Map looking to boost exploration in the UKCS, focus is being paid on underexplored plays such as the Palaeozoic. With the use of CGG's Q30PH7 BroadSeisTM and BroadSourceTM PSDM survey, the presence and prospectivity of a Devonian play on the northern Mid-North Sea High and southern Central Graben is investigated. With the associated improved imaging at depth, due in particular to a broader bandwidth and stable low frequencies, accurate seismic interpretation with emphasis on tectono-stratigraphy was performed and the hydrocarbon potential was assessed. The area of study is documented as having proven oil fields (Auk and Fulmar fields), which target Permian and Jurassic reservoirs; however the Devonian remains underexplored, despite evidence of hydrocarbon indicators away from the Central Graben source kitchen. The Central Graben formed by poly-phase tectonics associated with rifting in the Permo-Triassic and Late Jurassic-to-Early Cretaceous subsidence, uplift and inversion. The survey area is affected by NNW-SSE, E-W and N-W orientated faults formed under three separate stress regimes. The structural geometry is influenced by pre-existing basement weaknesses resultant from the Caledonian Orogeny, Trans-European Fault Zone and reactivation during the Variscan Orogeny. Seismic interpretation, petrophysical analysis and basin modelling has been utilised to characterise two Devonian plays; the Kyle Limestone and the Old Red Sandstone. Several leads were identified using depth-structure maps, isopachs and attribute analysis. Probabilistic simulation was run on leads associated with the highest chance of success. One of the most encouraging leads identified in the Kyle Limestone is presented in this publication. The results of this study highlight the potential hydrocarbon prospectivity within the Devonian. However, key uncertainties regarding the main petroleum system elements, including Palaeozoic source presence, long lateral migration distances for Kimmeridgian sourced hydrocarbons, seal integrity, reservoir presence and quality carry high risk factors.

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Zechstein Carbonates Revisited – New Insights and New Chances for an Old Play

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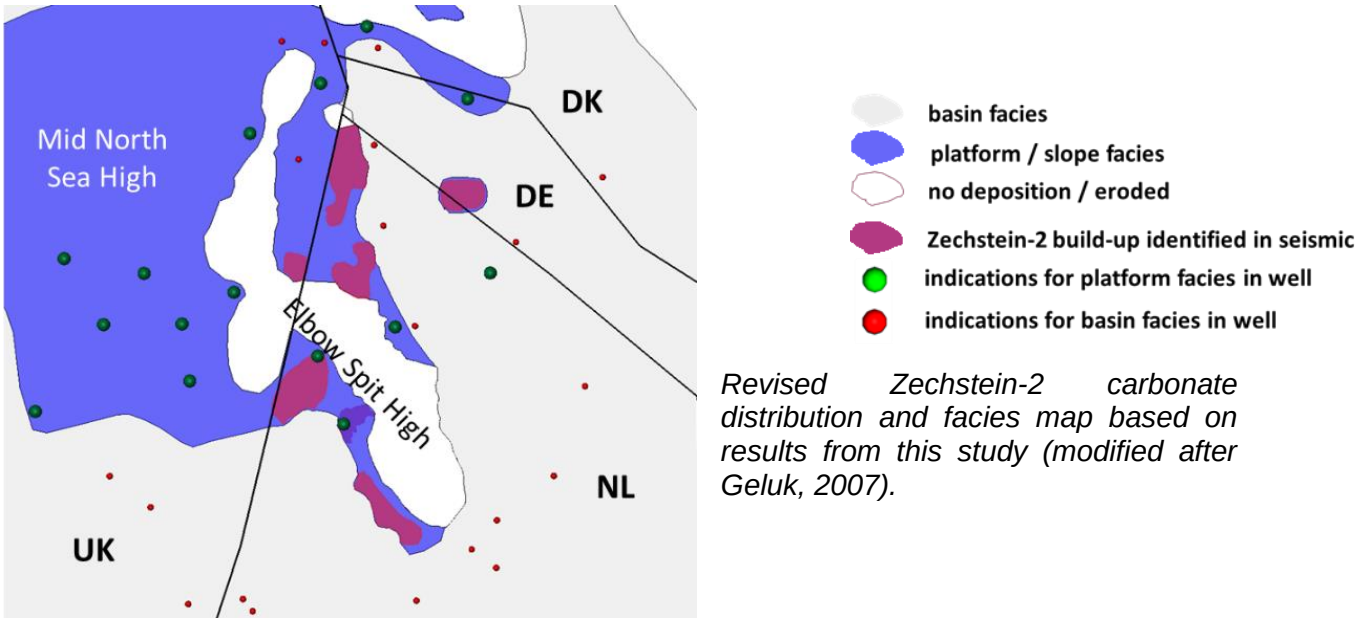
Hydrocarbons have been produced from shallow marine Upper Permian Zechstein carbonate reservoirs in the Southern Permian Basin (SPB) since the middle of the last century. These fields are situated along the western and southern fringes of the SPB; in the UK, the Netherlands, Germany and Poland.

In this studie we revisited the distribution of carbonates in the Zechstein-1 and Zechstein-2 cycles. Our review of well data from the Mid North Sea High (MNSH) area and the Cleaverbank High area shows that these carbonates developed in larger parts of the northern fringe of the SPB and with better reservoir quality than generally presumed. Recent 3D seismic data allowed for detailed mapping of the Zechstein section, leading to the identification of undrilled Zechstein buildups near the MNSH. Comparison with producing fields in the Netherlands and with outcrops in northeastern England led to a better understanding of post-depositional processes which may have impacted reservoir quality in the MNSH area by creation of collapse breccias. The findings were integrated to create new facies distribution maps for the Zechstein carbonates and to identify exploration prospects. Subsequent review of oil and gas shows and basin modeling indicates that the reservoirs could be charged from intra-Zechstein source rocks and from Lower Carboniferous coals.

Production data and well tests from Zechstein carbonates in the Netherlands show significant differences in producibility and recovery factors, resulting from the heterogeneity of these rocks. Analyzing basin-wide variations in controlling factors such as paleogeography, faulting, burial history and the position relative to the dominant wind direction, has helped in understanding the heterogeneity in producing fields and in predicting the heterogeneity in undrilled structures.



Revised Zechstein-2 carbonate distribution and facies map based on results from this study (modified after Geluk, 2007).

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NOTES

Controls On and Consequences of Upper Permian Carbonate Platform Margin Palaeomorphology in the Southern North Sea

Ross J. Grant [1], John R. Underhill [1], Rachel Jamieson [1] & Steven M. Barker [2,3]

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The UK Southern North Sea basin (SNS) is a prolific hydrocarbon province. The main play in the region involves Permian (Rotliegend) clastic reservoirs sealed by a thick Upper Permian sequence of alternating evaporite and carbonate layers (Zechstein Group). Strong lateral and vertical variations in velocity between anhydrite, dolomite and halite within the Zechstein are well known to cause seismic imaging and depth conversion uncertainty, and are the main challenges when interpreting and understanding seismic data in the region.

This study makes use of 1484 km2 of high-quality 3D time-migrated seismic data along the SW edge of the basin. Careful mapping of intra-Zechstein sequences has revealed the palaeomorphology of a deeply buried Zechstein Group (Z2) carbonate shelf margin consisting of a series of corrugated embayments and promontories which locally have relief in excess of 200 m. Use of petrophysical well-log and core data has permitted facies models to be devised that, when integrated with the mapping results, have led to a detailed understanding of the Zechstein shelf-edge geology.

Our studies show that the recognition of the Zechstein shelf edge's 3D physiography has significant impact for understanding prospectivity and delineation of the prospective reservoirs that lie below. The realisation that the Zechstein margin was more complex has led to more accurate definition of Rotliegend prospects including GDF's discovery of the Juliet field (47/14b). This recent discovery, now in development, reveals that the Upper Palaeozoic play fairway is more extensive along the basin margin than previously thought.

The results have significant implications not only for our understanding of basin margin carbonate slope systems such as the contemporaneous Guadeloupe Mountains of the Permian Basin in West Texas & New Mexico, but also for the evolution of the SNS and future exploration in the area. It is anticipated that this work may help extend the life of this mature yet prolific gas province by delineating further potential traps and new plays.

NOTES

The Lower Palaeozoic Petroleum System of the Oslo Graben and Its Relevance for the Petroleum Potential of the Skagerrak Graben, Offshore Southern Norway

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The onshore Oslo Graben rift basin is located in south-east Norway. The pre-rift stratigraphy includes Cambrian to Silurian marine sediments and Late Silurian to Carboniferous continental deposits. The Cambro-Silurian sedimentary rocks were buried and deformed during the Late Silurian to Early Devonian Caledonian Orogeny.

Rifting and volcanism formed the Oslo and Skagerrak grabens in Late Carboniferous to Permian time, and the pre-rift stratigraphy was covered with large volumes of extrusive volcanics. Today the Oslo Graben continues southwards into the offshore Skagerrak Graben, which is covered by Mesozoic and Tertiary overburden.

Cambrian-Ordovician hydrocarbon source rocks (marine mudstones) and Cambro-Silurian reservoir rock candidates (sandstones and carbonates) are present in the Oslo Graben. The source rocks matured in a foreland basin setting during the Caledonian Orogeny. Hydrocarbons have been sampled at several outcrop locations in the Oslo Graben; from a Cambrian sandstone, Upper Ordovician carbonate rocks, and a Permian volcanic intrusive. Hydrocarbon samples appear as solid bitumen, light oil and gas, and represent a Lower Palaeozoic petroleum system now extinct in the Oslo Graben.

This presentation describes occurrences of petroleum in the Oslo Graben and discusses the petroleum potential of the Skagerrak Graben based on data from outcrops and offshore shallow boreholes. Geochemical data is combined with seismic mapping and basin modelling in an investigation of a possible Palaeozoic petroleum system in the Skagerrak Graben. Onset of hydrocarbon migration versus time of trap formation and retention of trapped hydrocarbons are key risk elements.

NOTES

The Petroleum Geology of the Devonian in the Central and Northern North Sea

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This talk provides the authors of the Devonian Chapter of the Millennium Atlas an opportunity to present an update of the key highlights of the chapter.

A significance advance in the Atlas was the recognition that intervals attributed to the pre-Kupferschiefer Permian were in fact Devonian in age. This included the key correlative level of the Devonian Eday Marl Formation. Palynostratigraphic evidence will be presented for these correlations. Key sections from the Moray Firth will also be presented to demonstrate how applying these 'new' and consistent criteria to separate the Devonian and Rotliegend gives a geologically realistic distribution of stratigraphic units that ties with basin structure.

These findings are integrated with other evidence that demonstrates the proven and potential capability of the Devonian to provide hydrocarbon resources from the North Sea.

NOTES

Palaeozoic Geology and Prospectivity of the East Shetland Platform (UKCS Quadrants 3, 8, 9, 14, 15, 16).

Stefano Patruno, William Reid, *PGS Reservoir Limited, Weybridge, United Kingdom*

Despite significant discoveries within predominantly Paleocene-age reservoirs (e.g., Mariner), exploration activity in the East Shetland Platform region (ESP) has declined since the 1990s. Mesozoic packages are thin or absent whilst Palaeozoic reflectors were typically poorly imaged on older seismic datasets and sometimes mistaken for basement. Recent 3D dual-sensor towed streamer broadband surveys covering ≈17,500 km2 over parts of the UKCS Quadrants 3, 8-9, 14-16, have eventually allowed for clear imaging of the Palaeozoic reflectors. Here, 3D seismic interpretation and well analyses (e.g., backstripping) are combined to unravel the complex structural history and highlight the exploration potential of this large under-explored region.

Pre-Cretaceous horizons have been mapped over the entire area. We interpret a history of repeated tectonic inversions, which left behind up to four regional unconformities. On persistent platform highs these merge into fewer, composite erosional surfaces. Elsewhere on the ESP, predominantly subsiding mini-basins contain a nearly continuous Palaeozoic-Mesozoic succession.

Multiple pre-Jurassic plays have been identified, with viable source/reservoir/seal/trap systems. Structural/combination traps are often truncated by the Base Cretaceous Unconformity and sealed by overlying Cretaceous-Cenozoic mudstones. On and around the ESP, Permian-Carboniferous carbonates and sandstones, fractured Devonian sandstones and crystalline basement have all been successful targets in the past. The largest producing fields contain 100-1000 MMboe total recoverable (e.g., Buchan, Clair, Auk), highlighting the regional exploration potential of Palaeozoic reservoirs.

The ESP source rock is not properly understood. Hydrocarbon charge could be delivered by lateral migration from ‘traditional’ Upper Jurassic depocentres. Additional charge may be provided by vertical/lateral migration from oil-prone Devonian source intervals (c.f., Beatrice Field). Burial history modelling suggests that the best-case scenario (late generation/expulsion from the Devonian) occurred over parts of the region. This supports previous geochemical analyses, which postulated possible Devonian contributions for the oils of major fields near the ESP (e.g., Claymore, Piper, Tartan, Buchan).

NOTES

An Overlooked Play? Structure and Stratigraphy of the Carboniferous of the Greater Irish Sea Area

Tim Pharaoh, Nigel Smith, Colin Waters, Karen Kirk, Martyn Quinn, Oliver Wakefield. *BGS Keyworth.*

As part of the 21st Century Exploration Roadmap's Palaeozoic project, the Carboniferous structure and stratigraphy of the UK sector of the greater Irish Sea area is being reviewed using all available well and seismic data. The present economic focus of the province is the Morecambe Bay gasfield and its satellites, located within the Eastern Irish Sea Basin. The Bowland Shale Formation has been a prolific source of gas for the Permo-Triassic reservoirs, but potential Namurian and Westphalian reservoirs likely suffer from low porosity and permeability due to the combined effects of Variscan inversion, deep burial in a Permian-Mesozoic rift, Cenozoic inversion, magmatism and thermal effects associated with the rifting of the North Atlantic. The North Channel, Solway and Peel basins also contain Permo-Triassic strata, but are interpreted to have been less deeply buried than the EISB. Extensive 2D seismic datasets cover these areas. There have however been no economic discoveries, reflecting absence of a regional seal comparable to the Mercia Mudstone Group and evaporites in the EISB. Very limited well provings do not presently allow a full assessment of the prospectivity of the Carboniferous strata underlying these basins. Several areas on the margins of the EISB (Manx-Furness Ridge, Cumbrian margin, Fylde margin, Cambrian margin) are underlain by the offshore extensions of onshore coalfields or Namurian shale strata. These areas are covered in some detail by seismic data, and the availability of onshore analogues should facilitate an assessment in terms of potential for development of non-conventional resources. Finally, in Quadrant 109, there is an extensive platform lying between the Isle of Man and Anglesey, poorly covered by seismic and lacking well control. It is inferred to comprise c.5 km deep folded Visean and Namurian strata, but little is known about regional reservoir geometry, characteristics, intra-formational seals or structural closures. This area should therefore be a future target for regional seismic acquisition, as it offers potential for conventional and unconventional prospectivity in a Carboniferous play.

NOTES

Poster Presentation Abstracts

Prospectivity of the Early Carboniferous West Lothian Oil-shale Formation in the Midland Valley of Scotland

Miles Newman, *Reach CSG*

The Scottish Shale Oil Industry dates from the 1850s when James “Paraffin” Young started to produce oil products by retorting oil shale in West Lothian. 75 million barrels of oil were produced over a hundred years. The gas from the shale was used to heat the mined shale to produce this oil and in 1860 Bathgate became the first town in the world to be supplied with natural gas.

The shale oil works created demand for oil products such as paraffin for lighting and cooking. International demand for these Scottish products resulted in the first oil well being drilled in Pennsylvania in 1859.

The West Lothian shales produced over 2 million barrels of oil a year during the First World War and demand for oil was so great that the first oil wells in the UK were drilled at the very end of the War. Oil was discovered near Dalkeith and gas at West Calder in 1919. Gas was discovered at Salsburgh near Airdrie in 1945 and a well was drilled in Glasgow in 1989 that flowed 2.2 million cubic feet of gas a day on long term test. Both these wells were hydraulically fractured.

The rocks that produced this are those of the West Lothian Oil-shale Formation of Early Carboniferous age. These oil-shales, claystones, marls and limestones were deposited in the lacustrine environment of Lake Cadell. The kerogen type is mixed but largely Type 1 in the hyper-rich oil-shale seams and derived from an algae of the *Botryococcus* genus much like those responsible for present-day algal blooms in lakes of the East African rift valley.

These rocks are mature for oil and gas at quite shallow depths due high heat flow in the Late Carboniferous and uplift in the Tertiary. The Salsburgh 2 well drilled on Reach acreage PEDL 162, penetrated a full sequence of West Lothian Oil-shale at depth where it is oil and gas mature. Extensive proprietary geochemical on the cuttings from this well has proved moveable oil is present in the pore space. This is supported by the electric logs. Thermal extract chromatography has shown this oil to be light and generally non-waxy. Porosity measurements from near-surface, civil engineering cores at the outcrop of the West Lothian Oil-shale Formation has shown a porosity of approximately 7%. At depth, where the kerogen is oil mature, significant additional organic matter porosity is observed. XRD work indicates that the sequence can be hydraulically fractured to enhance permeability.

Operationally, the area of PEDL162 contains excellent infrastructure of road, rail, gas and oil pipelines and electrical supply. There are numerous and extensive brownfield sites which are the legacy of the coal mining and quarrying industries that were active here in the 20th century.

This area of the Midland Valley between Glasgow and Edinburgh will provide the perfect location for an initial assessment of the unconventional oil and gas prospects for Scotland.

Understanding the Distribution of Organic Matter in the Bowland Shale

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A key question for understanding and assessment of potential UK shale gas resources is what controls the distribution, abundance and type of organic matter that is preserved? The Bowland Shale (late Mississippian), deposited in a marine epicontinental basin, has potential as a UK unconventional hydrocarbon resource. There are, however, few legacy boreholes with core through the Bowland Shale Formation to address this question, but exposures across Lancashire and Yorkshire provide excellent spatial coverage. Data from these sites will provide insights into the controls (sedimentological, biological, geochemical) on the spatial distribution of organic matter in approximately time-equivalent sample locations. We have developed a strategy for sampling fresh material from outcrop to ensure our data are unaffected by modern weathering.

In a 124 m thick exposed succession of the Bowland Shale, located in the Craven Basin, Lancashire, we delineate variations in lithology, organic geochemistry (including total organic carbon (TOC), RockEval (RE) and carbon isotope analysis (δ13C)), palynology and inorganic geochemistry (e.g., x-ray fluorescence). Analyses from these outcrop samples are compared with time-equivalent borehole core samples also from the Craven Basin.

From the Lower Bowland Shale to the base of the Pendle Grit, the dominant mudstone lithology is interbedded with decimetre scale, carbonate-cemented silty to fine sandy turbidites likely representing at least 40 events. Preliminary data indicate mudstone TOC ranges between 4 to 6 wt. % and comprises dominantly Type I algal material (RE data), with exceptionally low oxygen index (OI; typically < 10). Palynological and δ13C results corroborate the RE data, which indicate a dominance of amorphous organic matter (AOM). A range of sedimentary and water column processes, identified through interpretation of sedimentological and inorganic geochemical data, enable the burial and preservation of large volumes of organic matter in these basinal settings.

Unconventional Palaeozoic Hydrocarbons in the United Kingdom: An Assessment of Petroleum Systems through Chronostratigraphy

Emily Rees and Owen Sutcliffe, *Halliburton,*

The onshore petroleum systems of the UK have not been in doubt since oil and gas seeps were identified on the surface and in coal mines as early as the 1700s. These conventional petroleum systems have been worked by small and large companies alike, to varying degrees of success, but always targeting shallow Mesozoic structures. With the advent of more advanced exploration tools and the increases in seismic resolution, there is a shift of focus to Palaeozoic plays, not only for conventional accumulations, but unconventional sources as well.

The Bowland Shale is a known organic rich horizon in the Carboniferous of the partly onshore Bowland Basin of the UK. The basin formed during a period of extension, which created several grabens across the UK with intervening topographic highs. These highs restricted water circulation and allowed for the deposition of organic rich material within deepwater shales, known across the UK and Ireland as the Bowland, Edale, and Holywell shales. These horizons are known source rocks for oil accumulations of the Irish Sea, Cheshire, East Midlands, and West Lancashire basins, but current interest focuses on their unconventional potential.

By taking a look at the development of the Carboniferous basins in the UK in a chronostratigraphic framework, an understanding of depositional history can be developed for the Bowland Shale. This presentation highlights how the depositional environment, tectonic evolution, and regional drainage patterns of the UK during the Carboniferous majorly influenced the development of this important organic rich formation, and provides insight into how to predict where these systems might occur in other similar basins across the UK.

Basement Reservoir Plays: Pros, Cons and Maybe's

Jon Gutmanis, *GeoScience Ltd, Falmouth Business Park, Bickland water Rd, Falmouth TR114SZ, UK*

This presentation will review the key geological, geomechanical and hydraulic factors that determine whether basement plays are commercially viable. We will deal primarily with crystalline rocks of Palaeozoic and older age including extrusive, plutonic and metamorphic lithologies, with a sideways look at Palaeozoic carbonates and clastics for comparison.

Given their generally tight matrix properties, reservoir quality is strongly dependant on secondary porosity from natural fracturing and also, in carbonates, from karstic and related dissolution processes. A variety of fracture types are capable of providing the necessary storage however the key aspects are firstly the timing and mechanism of hydrocarbon charging relative to fracture porosity development, and secondly the degree of geometric and hydraulic connectivity in the fracture system. The first of these may lead to unusual hydrocarbon distributions, and the second is important for sustainable production.

Although there have been and are some important reservoirs and good production from basement reservoirs we suggest that they are not straightforward to explore and develop due to the factors above and also due to the challenge of acquiring good quality seismic imaging of the fractures and faults within them. Nevertheless they should not be overlooked as has commonly been the case in the past.

A Palaeozoic – Caenozoic Structural Framework for the Mid North Sea Area

Marten ter Borgh, Bastiaan Jaarsma and Eveline Rosendaal, *EBN B.V. Daalsesingel 1, 3511 SV Utrecht, the Netherlands.*

Recent gas discoveries north of the proven Rotliegend and Carboniferous fairways have caused an increased interest in the Mid North Sea (MNS) area. To assess the hydrocarbon potential of this structurally complex area a sound understanding of its structural evolution is required. We used new high quality 2D and 3D seismic data covering the Dutch northern offshore to develop a structural framework for Palaeozoic to recent times.

Early Carboniferous extension was accommodated predominantly along WNW-ESE trending faults and was characterized by an alternation of highs and lows; in the northern Dutch offshore the principal high coincides with the present-day Elbow Spit Platform (ESP). An Early Carboniferous low is present north of this high in the A and B quadrants. Lower Carboniferous deposits have been preserved in this low and on the ESP and mature source rocks may be present.

Late Carboniferous and Early Rotliegend deformation is accommodated primarily along normal faults with a NE-SW trend. These faults commonly show no significant offset of Upper Rotliegend and younger units. Development of the Dutch Central Graben and Step Graben occurred during the Triassic to Jurassic; primarily along N-S trending faults, but reactivation of pre-existing faults as oblique-slip faults occurred as well.

Another, not previously described family of faults was active during the Jurassic to Early Cretaceous, with minor later reactivations. Deformation occurred primarily along WSW-ENE trending dextral strike-slip faults; conjugate strike-slip faults are present locally. During this phase pop-up and pull-apart features with trap potential were formed. As a result of decoupling within the Zechstein salt these faults occur only in units below the salt, and in units above the salt in areas where the salt was absent or thin.

The structural framework is used to assess the hydrocarbon potential of the Dutch northern offshore, with promising results.

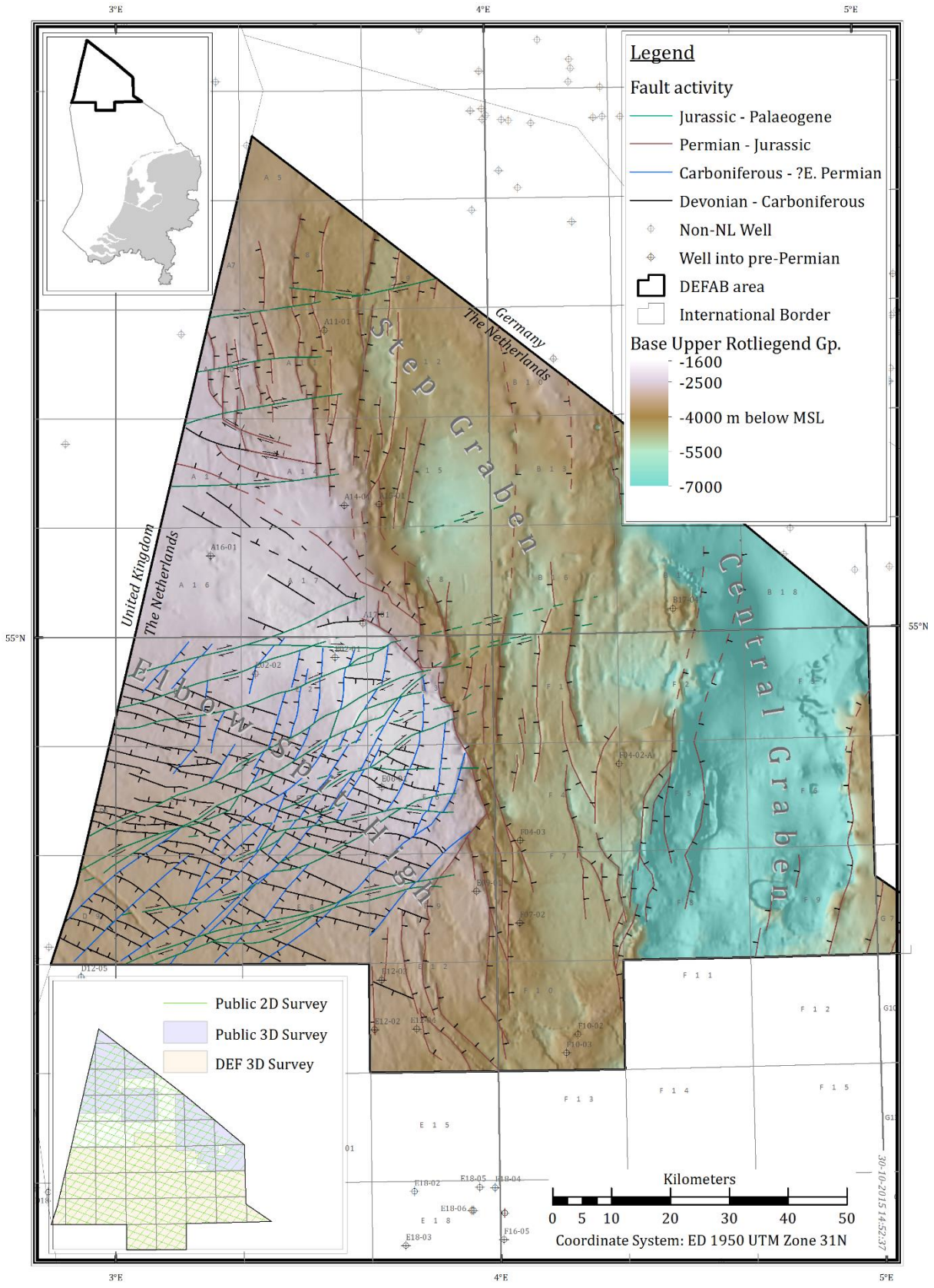

Figure: structural framework for the northern Dutch offshore. Faults are shown at Base Permian level, except in blocks D9 to E9, where faults are shown at Top-Visean level.

The Carboniferous Bowland Shale Formation (UK): Understanding the Sedimentological and Diagenetic Processes within a potential Shale Gas Exploration Play

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The Bowland Shale Formation of northern England, a succession of Carboniferous organic-rich mudstones, is the proven source rock for both onshore and offshore conventional hydrocarbons and a major focus for shale gas exploration in the UK. The sedimentological and diagenetic variability within the succession will likely play a major role in controlling reservoir quality, but current knowledge is limited, leading to significant uncertainty for exploration.

The Bowland Shale was deposited in a series of interconnected (half) graben basins in the Pennine Province, northern England. This study focuses on 65m of previously undescribed core within a marginal to basinal succession from the Bowland Basin and documents the scale and nature of microfacies compositional and diagenetic variability. A detailed microfacies scheme was constructed using scanned thin sections, optical microscopy and high resolution SEM images based on texture and composition, and refined through consideration of physical sedimentary structures, biogenic sedimentary features and diagenetic products. Five facies have been identified, a change in the dominant facies occurs from calcareous mudstone in the Lower Bowland Shale to argillaceous mudstone in the Upper Bowland Shale. Common diagenetic features are clay and carbonate cements (siderite, calcite, dolomite, kaolinite and illite) as well as extensive framboidal pyrite typically associated with organic matter. Organic geochemical analyses (TOC and RockEval™) were integrated with microfacies observations to reveal key associations between organic matter type and richness with the depositional framework.

The transition from a carbonate-rich to clay-rich system recorded within the facies coincides with the reduction of carbonate material into the basin due to sea level rise resulting in the drowning of the surrounding carbonate shelves. The sedimentology and diagenetic alteration of the succession are both strongly influenced by the tectonostratigraphic setting. This research has a significant impact on the generation of predictive geological models, within this unconventional reservoir.

Reservoir Properties of Lower Carboniferous Mississippian Limestone of the Derbyshire East Midlands Platform

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There has been significant interest in the Mississippian limestone of northern Europe as a secondary reservoir target over a number of years. Most of these studies have concluded that although hydrocarbon is present, permeability is poor and hence reservoir potential is negligible. Comparatively little focus has been on the localised bodies of dolomite, however. This study uses a multi-scale approach to reservoir characterisation, using outcrop, borehole core, thin sections, wireline logs and outcrop petrophysical analysis to investigate evidence for the timing and mechanism for dolomitisation and its impact on reservoir quality.

Fault-controlled dolomite has been well studied and described in various localities in the Pennine Basin and North Wales [1,2,3]. This study focuses upon the Derbyshire Platform which is a Mississippian rimmed shelf, the westernmost expression of the East Midlands Platform. On the SE platform margin, 50km^2 of Visean limestones have been dolomitized, forming two major bodies associated with major NW – SE trending basement lineaments and volcanics. The dolomite hosts calcite-cemented fractures and Pb-Zn-F-Ba mineralization, which are associated with minor quantities of hydrocarbons, interpreted to have formed during the Variscan Orogeny.

Dolomite is weakly fabric retentive to fabric destructive and comprises a range of textures that suggest multiple phases of fluid flux. The limestone contains little or no visible porosity, due to calcite cementation and stylolitisation. Geochemical data indicates dolomitisation from slightly modified seawater, with a contribution from hydrothermal fluids sourced along faults and fractures. Based on plug-scale core analysis, the best reservoir properties are in dolomitised sections (19.25% Φ, 5.093 mD). Unaltered limestone displays significantly lower porosity (2.22 - 2.29% Φ) and permeability (0.010 - 0.014 mD). It is suggested that a combination of facies control and the type of karstic surface affects the development of reservoir and remains a key uncertainty.

The Palaeozoic Petroleum System in the North of Scotland - Outcrop Analogues

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All the components of an active Devonian petroleum system can be found onshore in the Orkney Islands. We will demonstrate each element from a good quality mature source rock to a bitumen bearing sandstone reservoir with at least ± 2.5 billion barrels of oil in place. Several such reservoirs exist on mainland Orkney. Active oil shows have been reported commonly associated with faults. Anecdotally, a 3 day “gas blowout” was reported in WWII when a deep water well was drilled on Shapinsay.

Source rocks consist of 0.5 m - 20 m thick organic rich lacustrine laminites (fishbeds). These fishbeds represent some 20% of the sedimentary cycles within Lake Orcadie. The Middle Devonian flagstones cycles have 108 such cycles which were controlled by Milankovitch short eccentricity (100 ka).

RockEval oil show analyser and vitrinite reflectance measurements indicate that the organic matter is good quality TYPE-I and II kerogens and within the early oil window on mainland Orkney. These source rocks underwent burial until the Permian structural inversion brought these rocks to the surface. Earlier timing and greater maturity would have existed offshore to the west and east.

The reservoir rocks consist of aeolian and fluvial sandstones with porosity in the range of 15% to 25%. These reservoirs have been “breached” losing all the light end hydrocarbons leaving pore space bitumen residues. Thin fluvial sands and sheet-floods 10 cm - 50 cm thick within the flagstone cycles also have bitumen residues in the pore space and although not potential targets do provide permeable connectivity between the thicker sandstone reservoir units.

Sealing formations consist of the lake laminites (both source and seal), mudstones, flagstones and volcanics.

All types of trap are found. Principally the major broad anticline running north-south on mainland Orkney. Also present are an unconformity with fault traps and pinch outs.

Determination of the Processes Governing the Architecture of Carboniferous Platform Margins, Northern UK

Lucy Manifold[1], Prof Rob Gawthorpe[1], Dr Cathy Hollis[1], Dr Irina Korneva[2], Prof Atle Rotevatn[2], Dr Stefan Schroeder[1]

[1]*The University of Manchester, Carbonate Petroleum Geosciences*
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The aim of this new project is to assess the interplay of structural, depositional and diagenetic processes on platform margin architecture, to improve reservoir quality prediction within Carboniferous carbonate platforms. Such platforms are the main reservoir in giant oil and gas fields of the Precaspian Basin, but facies architecture, syndepositional fracturing and diagenetic overprint can contribute to complex, heterogeneous and multiscale pore networks[1]. In northern England, Mississippian (uppermost Visean, Asbian-Brigantian) flat-topped carbonate platforms formed during reactivation of pre-existing structural lineaments as normal faults[2]. This study is focused on the Derbyshire Platform, northern England, and the North Wales Platform. These relatively small, but accessible, outcrops provide the opportunity to describe the platform margin and thereby the influence of normal fault growth on facies distribution, platform growth and diagenesis.

Preliminary field mapping and geophysical imaging defines a complex array of facies. The margin is dominated by microbial build-ups (metres to tens of metres in diameter), with well-defined core- and flank facies, and skeletal and oolitic grainstone shoals. Behind this margin, platform interior Asbian limestones comprise stacked, upward-shallowing crinoidal packstone-grainstone facies, capped by exposure surfaces. At the end of the Asbian, a well formed and correlatable palaeosol indicates that the platform top was exposed, potentially by footwall rotation. Overlying, Brigantian, strata are dominated by brachiopod-rich packstones with abundant chert, reflecting a change in water turbidity prior to platform demise. Throughout the Visean, the platform slope is characterised by reworked of lithified platform margin sediment within metre-scale slumped and channelized bodies.

This poster will present results from initial fieldwork, providing quantitative data as to the shape, size and distribution of depositional and structural geobodies. A preliminary assessment of the influence of faulting on platform margin architecture and facies distribution will be presented, and the reservoir potential of the platform margin assessed.

1. Collins, J., et al., 2006, Facies and reservoir quality variations in the late Visean to Bashkirian Outer platform, rim and flank of the Tengiz build-up, Precaspian Basin, Kazakhstan. AAPG Memoir, 88, 55-95
2. Fraser, A. and Gawthorpe, R., 2003, Geological Society of London Memoir, 28

Palaeozoic Plays in South Wales

Steven Bushell and David Barker, *Sonorex*

Onshore Licences PEDL 157 & 224 were acquired over an unexplored part of the UK. Sonorex's proprietary 2D, tied to a neighbouring well and seismic data, has revealed a New Play Concept for oil and gas exploration in the UK.

Multiple Palaeozoic reservoirs and source rocks.

A large Drill Ready structure, the Newport Prospect, is a pre-Permian anticline of Carboniferous to Cambrian strata identified by well ties to excellent seismic reflections in excess of 11,000 feet.

Conventional sandstone and limestone reservoirs could have been charged by older Palaeozoic sources common to un-deformed basins around the world. Shale gas potential may also exist.

A very thick Old Red Sandstone (Devonian), enhanced by fracturing, offers 1,200ft (365m) of quartz-rich, porous (5-7%) reservoir (c.f. Buchan field). Deeper targets are offered by the Wenlock and Woolhope limestones (U. Silurian), algal reef formations interbedded with shales and sandstones. A 5,000ft (1520m) vertical well will test all three reservoirs. The faults that formed the Newport Anticline would also act as conduits from the deeper source rocks.

Potential hydrocarbon sources are offered by mudstones and shales in the Upper and Lower Silurian (Ludlow and Llandovery) and the even earlier Cambro-Ordovician (Tremadocian). Silurian gas shows were encountered in the Usk-1 well 12km north of the licences, and the Llandovery may be in excess of 1,000ft (300m) thick in the Newport Prospect. Tremadocian black shales with high TOC values crop out in the Malvern Hills further north and could offer additional gas source potential.

The large Palaeozoic basin of the Welsh Borderlands extends southwards across the Sonorex licences and deepens into the localised Bristol Channel Basin, identified by gravity data and confirmed by seismic penetration to over 1.8 secs (4200m) (14,000ft).

Contemporary with hydrocarbon producing Lower Palaeozoic basins in North Africa and the Baltic, the Bristol Channel Basin bears remarkable similarity to the Utica Platform adjoining the Appalachian Mountains. Although on a smaller scale, it also is a moderately un-deformed Foreland adjacent to a regional Variscan Front.

Maturation history indicates exhumation and erosion was limited to the Late Carboniferous – Early Permian (Hercynian epoch). Hand specimens and literature review suggest Lower Palaeozoic burial depths in excess of 14,500ft (4200m) provided adequate thermal maturity to generate oil and latterly gas from Type II and III source rocks.

Unconventional Shale Gas potential might exist on the Newport Prospect in the Upper and Lower Silurian formations where over 2,700ft (800m) of Ludlow and Llandovery shales may be present.

The Upper Permian Gohta Discovery: The Kick Start for a New Discovery Trend in Late Palaeozoic Carbonates of the Norwegian Barents Sea

Harald Brunstad and Trond Kristensen, *Lundin Norway AS*

The Upper Palaeozoic carbonates of the Barents have been recognized as an exploration play since the late 1970's. Several wells have been drilled to investigate the play, but it is only recently that it has been proven to contain potentially commercially sized trapped hydrocarbon volumes.

Early exploration focused on seeking karstified Upper Carboniferous-Lower Permian warm-water carbonates of the Ørn Fm and upper Permian cooler-water spiculitic carbonate platforms of the Røye Fm. The Gohta structure was first drilled in a downflank location by well 7120/1-1 (1985) which found tight carbonates in the Røye formation, with oil shows. Lundin and partners, Det Norske and Noreco identified untested up dip potential in truncated, potentially karstified porous carbonates of the Røye Fm. Before drilling of the Gohta prospect, there was skepticism about the capability of these cool water, chert rich carbonates to develop porosity and permeability of any significance.

Lundin's 2013 Gohta discovery found an oil leg with a gas cap in the Upper Permian Røye Fm with extensive coring and testing of the well demonstrating good quality reservoir with significant test rates, strong indications of karst development and dissolution porosity in mixed carbonates and chert. The porosity seems to be a result of repeated exposure during multiple periods of relative sea level fall, mainly because of tectonic uplift during the Permo-Triassic rifting.

This is the first time that karstified, porous Røye Fm is documented. Since the karstified cherty carbonates of the Røye Fm is a completely new sub play, much investigation is still necessary to understand its reservoir development. Thanks to the Gohta discovery, exploration for the Late Palaeozoic carbonates has gained a renewed interest by numerous players in the Norwegian Barents Sea and also in other related geological provinces such as the Sverdrup Basin in Canada.

Acknowledgements to collegues in Lundin Norway AS, Noreco and Det Norske AS.

Palaeozoic Sourced Oil Play In the Jura Mountains of France and Switzerland

Christopher P Pullan[1] and Martin Berry[2]

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The La Chandeliere oil discovery in 1988 opened up a Triassic oil play in the Jura Mountains of France and Switzerland. The Jura fold belt is an arcuate shaped fold and thrust belt which developed during the Mio-Pliocene. Both thick skinned tectonics of the pre Triassic basement as well as thin skinned tectonics of the post Triassic section is recognised with Triassic evaporite distribution controlling deformation of the post Triassic section.

The oil was encountered in the Triassic Bunter Sandstone, which was deposited in a non-marine fluvial environment. In the area of the La Chandeliere Field the sands are 14-17m thick with average porosities of 12%. However, well data shows that, regionally, the sands thicken towards the northeast into Switzerland. The interval is sealed by the overlying shales and evaporates of the Triassic Muschelkalk and Keuper intervals. The underlying Permo-Carboniferous sandstones represent a secondary exploration objective.

The generation of oil has been demonstrated by the discovery at La Chandeliere. However the widespread generation of both oil and gas is demonstrated by the surface hydrocarbon seeps in the Jura region as well as the gas discoveries at Valempoulieres and Lons Le Saunier. Rich oil prone source rocks are developed in the lacustrine sequences of the Permian (Autunian) and Upper Carboniferous (Stephanian) sequences. Additional gas potential exists from interbedded coals. Maturity modelling is made complex due to the uncertainties in the estimation of the Tertiary uplift. The results suggest that the source rocks entered the oil window in the southern Jura in the Lower Cretaceous with peak generation in the Late Cretaceous.

The La Chandeliere structure is a northeast-southwest trending anticline which, at reservoir level, is bounded to the northwest by a normal fault zone. This anticlinal trap was formed by northwest directed thrusting and lies below an over-thrusted package of post Upper Triassic sediments in the northwest.

This model of the Triassic Bunter Sandstone, and older Permo-Carboniferous reservoirs charged by Palaeozoic source rocks and sealed by Triassic salt is an unexplored exploration play within the Jura fold and thrust belt through France and Switzerland.

Devonian-Carboniferous Back-Arc Extension in Avalonia and Its Impact on 350 Ma of Basin Evolution

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The Devonian-Early Carboniferous was a period of intense rifting in the Avalonia microplate in between the Caledonian and the Hercynian-Alleghanian collision phases. This rifting phase created the typical horst-and-graben structure of much of East Avalonia's crust that is best known from the UK and Ireland where the horsts and the graben infill are located at or near the surface. In the Southern North Sea, the Netherlands and northwest Germany, the Late Devonian-Early Carboniferous rift structure and units are obliterated by the thick cover of Late Carboniferous-to-Recent basin fill and by the recurrent fault reactivation. Although this rifting created the basis for 350 Ma of lithospheric memory, its dynamics remains relatively unknown. Major open questions include the mode and total amount of extension as well as the age and origin of the Central Graben and the relation between structures located east and west of it.

This study addresses these issues by integrating existing data from lithosphere to basin scales and a map-view restoration. We have revised the crustal map of the Thor Suture Zone. The newly defined northern margin of Avalonia and the Thor Suture Zone are key elements in the reconstruction of Devonian-Carboniferous rifting of Avalonian lithosphere. We present a revised map of Devonian-Carboniferous basin structures including the main horsts and grabens and the governing faults east of the Central Graben.

Based on these maps, we present a new paleotectonic reconstruction and a novel geodynamic scenario for the Devonian- Carboniferous rifting. These findings are key for better understanding of long-lived tectonic compartmentalisation and post-rifting deformation phases.

This research was sponsored by the Dutch TKI Gas foundation and the 2F2S programme with financial support from Baker Hughes, EBN, ENGIE, Total and Wintershall.

The Unexploited Potential of the Mid North Sea High (UKCS Quadrants 35-38, 41-43): Undrilled Carboniferous-Devonian Structural Traps and Zechstein-Age Inferred Carbonates.

Stefano Patruno, William Reid, Chris Davies, *PGS Reservoir Limited, Weybridge, United Kingdom*

The 'Mid North Sea High (MNSH)' region (UKCS Quadrants 35-38, 41-43) is a structurally elevated area, partly surrounded by basinal depocentres. These include the mature hydrocarbon provinces of the Central North Sea (CNS) to the NE and Southern North Sea (SNS) to the SE.

The MNSH region has been underexplored (1.2 wells/1,000 km2) due to the lack of Westphalian to Lower Permian source/reservoir intervals. Nevertheless, two recent Dinantian-age discoveries (Breagh/Crosgan) prove that a working pre-Westphalian reservoir is present, with potential for charge via lateral migration from the SNS Westphalian source kitchens.

Here we present the results of the interpretation of recent 2D and 3D seismic datasets over parts of UKCS Quadrants 36, 37, 42 and attempt to unravel both the geology and prospectivity of this frontier area.

The base of the Zechstein Group sits on a major unconformity, likely reflecting Variscan uplift. Below it, several WNW-ESE-trending fault blocks and faulted folds comprise pre-Westphalian Carboniferous reservoir packages and in addition the upper Devonian Kyle Limestone. In the study area, these anticlines and low-throw faults (modal plan-view length of 3-4 km) form undrilled closures.

A series of Lower Zechstein clinothems have been mapped and interpreted as an outbuilding of a carbonate/sulphate platform complex. These are equivalent in age to Z1-Z2 carbonate reservoirs in the CNS (e.g., Auk Field) and throughout the Southern Permian Basin.

The deformed Upper Zechstein evaporites do not appear to affect the underlying tabular, rigid unit. Below its topset, this unit has a near-uniform time-thickness, with maxima of 0.12 s TWT. A foreset-to-bottomset transition bounds this complex displaying plan-view bays and promontories. Further minor pinnacles can be interpreted away from the main bank. The presence of oil-prone anoxic bottomsets could be hypothesized (c.f., Polish BMB fields), to provide additional localised source.

The Devonian Lacustrine Source Rock Sequence in Canning Land, East Greenland

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The Main Devonian Basin in East Greenland contains a sand-rich sequence, largely fluvial in origin, which is late Mid Devonian to early Carboniferous in age. However, east of the Eastern Fault Zone there is a linked half-graben that includes an older Eifelian (early Mid Devonian) lacustrine succession that is present in both Vilddal to the north and on Canning Land and Wegener Halvø to the south. The Devonian rocks of Canning Land in East Greenland (71°N) are described in a modern synthesis and are clearly correlative in age, facies, palaeoenvironments and source rocks to the Orcadian Basin in Scotland. These source rocks are evaluated for extent, organic matter type, richness and thermal maturity. Within the exhumed hydrocarbon system pyrobitumens are abundant both in veins and within the source rock. These frequently have bimodal reflectivity distributions interpreted as indicating 2 phases of hydrocarbon generation. Importantly the Canning Land succession includes elements of the younger Palaeozoic and Mesozoic cover sequence that enables a more realistic vitrinite-constrained burial model. The Canning Land sequence is an important Devonian section as it extends the area of lacustrine deposition far to the north of the Orcadian Basin and its offshore correlatives.

The UK's Unconformity Maps Used for Assessing Basin Configuration and In Support Of Hydrocarbon Prospectivity

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Three main unconformities have been penetrated in hydrocarbon, coal and water boreholes in the UK onshore and offshore. These are the Acadian unconformity resulting from uplift and erosion following an early-mid Devonian orogeny, the Variscan unconformity caused by the late Carboniferous orogeny and the non-orogenic late Cimmerian unconformity of mid Cretaceous age. The effects of the orogenies extend beyond the foldbelts. Three GIS maps of each unconformity have been made, comprising the supercrop formation or age, depth below Ordnance Datum and subcrop formation or age. These maps provide regional evidence of the main Mesozoic and Upper Palaeozoic depocentres, hydrocarbon kitchens and inverted basins. The maps are based on a downhole 'Stratigraphic Surfaces Database' which BGS developed to integrate with seismic reflectors and 2 legacy Variscan maps which BGS produced for the forerunner of DECC in 1985. The database does not record verbatim either company final well reports or composites (which are fixed at the date they were originally produced) but includes any re-interpretations which are more likely to be consistent with all available data. The anomalies highlighted by the maps help to improve decisions on the best correlation of sequences above and below the unconformities, where weathering and secondary reddening can penetrate to greater than 500 m and indicate that some final well report sequences are improbable. The maps have been updated in more detail as areas have been re-assessed.

Key Challenges for Understanding Zechstein Carbonate Reservoirs in NW Europe

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Historically, Zechstein carbonate plays in NW Europe have had varying production success. The important influence of reservoir properties is illustrated by a comparison of the Ardmore, Auk and Dalen fields. Ardmore (once known as Argyll, now active as Alma) and Auk lie within the UK Central North Sea, have comparable Zechstein stratigraphy and both are in Quad 30 (ca. 40 km apart). Both fields have strong aquifer drive and Zechstein wells in both have a similar range of cumulative oil production volumes, with pressure depletion over the life of the fields. Whereas on Ardmore the spatial position of a well within the field has an impact on produced volumes, the volumes produced from Auk wells do not have a systematic spatial relationship. The Dalen field in the Drenthe province, onshore Netherlands, is very different from Ardmore and Auk. There is little evidence of aquifer support, only one well shows significant water production; production rates are relatively low and there is no evidence of pressure depletion. Understanding the connectivity of the carbonates is critical in explaining the observed differences.

Zechstein carbonates within the Southern Permian Basin, from the southern North Sea to Poland, have been widely studied, although peer-reviewed literature from different sub-basins includes sequence stratigraphic interpretations that are inconsistent across the whole basin. In the Northern Permian Basin, the central and northern North Sea are relatively under-studied, and there are still divergent opinions on facies assignation in cored wells (e.g. Ardmore and Auk fields designated as shallow-water facies by Trewin et al., 2003, and deep-water facies by Taylor, 1998).

Diagenesis in carbonate-evaporite systems is complex and can variously lead either to permeability reduction or enhancement: effects include lateral and vertical variation between limestone and dolomite, complex history of cementation, evaporite-filled fractures, and enigmatic diagenetic fabrics. Although diagenesis typically follows a particular path, prediction of porosity-permeability properties are difficult.

Another common challenge in most Zechstein carbonate reservoirs is that fracture permeability is significant for production. This can be associated with early water production, a relatively common occurrence for Zechstein carbonate reservoirs. Sometimes fracture permeability is higher or lower than anticipated, with significant impact for well (and field) productivity. Understanding the mechanical stratigraphy, in particular identifying any units which have pronounced fracture properties (either a tendency to retard fractures and act as a mechanical barrier, or units with a tendency to be highly fractured) will be useful in optimising development.

Brecciation is also common in Zechstein carbonate reservoirs, though is not encountered in every field. There are multiple causes of brecciation, including debris flows, karst, or collapse following evaporite removal. The significance of brecciation for fluid flow is dependent upon breccia body shape, degree of cementation, timing, and lateral and vertical extent. Understanding the cause of brecciation and any implications for breccia body permeability and extent can be beneficial.

To tackle these challenges, and improve our understanding of the key factors affecting the performance of Zechstein reservoirs, we have undertaken an extensive multi-disciplinary study involving integration and interpretation of new and legacy data from outcrops and sub-surface. World class Zechstein carbonate outcrops in NE England have been examined in conjunction with cored wells and production data to improve understanding of connectivity within Zechstein carbonates. In particular, the characterisation of fractures has been extensively documented through lidar, photogrammetric and field measurements, and analysed within their structural, stratigraphic and diagenetic context. A revised basin-wide sequence stratigraphic framework allows application of the derived mechanical understanding.

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