British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Palaeozoic Petroleum Systems of the Central North Sea/Mid North Sea High

Energy and Marine Geoscience Programme

Commissioned Report CR/15/124

BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCE PROGRAMME

COMMISSIONED REPORT CR/15/124

Palaeozoic Petroleum Systems of the Central North Sea/Mid North Sea High

A A Monaghan & S. Arsenikos, E Callaghan, R Ellen, C Gent, S Hannis, A Henderson, G Leslie, K Johnson, M Kassyk, T Kearsey, A Kim, G Kimbell, M Quinn, W McLean, D Millward, T Pharaoh, M Sankey, N Smith, C Ugana, C Vane, C Vincent, P Williamson

Keywords

Palaeozoic; CNS, petroleum systems.

Front cover

Core from well 43/17- 2 at 3170 m in sandstone and mudstone of the Millstone Grit Formation. BGS©NERC. All Rights Reserved 2016

Bibliographical reference

MONAGHAN A A AND THE PROJECT TEAM. 2015. Palaeozoic Petroleum Systems of the Central North Sea/Mid North Sea High. *British Geological Survey Commissioned Report*, CR/15/124. 105pp.

Keyworth, Nottingham British Geological Survey 2015

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh, EH14 4AP

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Requests and enquiries should be addressed to Alison Monaghan, 21CXRM Palaeozoic Project Leader, als@bgs.ac.uk.

Foreword and acknowledgements

This report is a published product of the 21st Century Exploration Road Map (21CXRM) Palaeozoic project. This joint industry-Government-BGS project comprised a regional petroleum systems analysis of the offshore Devonian and Carboniferous sequence in the North Sea and Irish Sea.

Project sponsors are thanked for data donations and their involvement at Technical Steering Committee meetings, both of which have contributed to this synthesis. John Collinson, Colin Jones and Peter Dolan are thanked for donation of commercial reports. Seismic companies (CGG, Dolphin, PGS, Spectrum, TGS, Western-Geco/Schlumberger) are thanked for allowing reproduction of selected seismic lines and for agreeing to the release of a set of 5 km resolution grids.

Christian Mathieu (OGA), Tiffany Parsons (Centrica), Paul Herrington (MOL UK) and Henry Allen (21CXRM) are thanked for technical review of this report.

Contents

FIGURES

TABLES

Summary

This report synthesises the results of the 21CXRM Palaeozoic project to describe the Carboniferous and Devonian petroleum systems of the Central North Sea/Mid North Sea High area (Quadrants 25–44).

Focusing on frontier areas to the north of the Southern North Sea gas fields and west of the Auk-Flora ridge, integration of a large volume of seismic, well, geophysical, organic geochemistry, maturity and reservoir property data at regional scale has established:

- Extensional to strike-slip Devonian and Carboniferous basins cutting across the Mid North Sea High on orientations strongly controlled by basement inheritance, granites and a complex Palaeozoic stress field. Varsican orogenic transpression and inversion was superimposed resulting in a variety of structural trapping styles and burial/uplift histories, and a complicated pre-Permian subcrop map.
- A widespread spatial and temporal extent of oil and gas mature source rock intervals within the Carboniferous succession particularly;
    - lower Carboniferous (Visean) coals and mudstones of the Scremerston Formation, dominantly fluvio-deltaic and lacustrine with some marine influence, dominantly gas prone. Gas mature in Quadrant 41 and central-southern Quadrants 42-44 and oil mature in the Forth Approaches and North Dogger Basin
    - lower-mid Carboniferous (Visean-Namurian) coals and mudstones of the Yoredale and Millstone Grit formations in fluvio-deltaic to marine cycles, gas prone with oil prone intervals. Gas mature in central Quadrant 41 and southern Quadrants 42-43, oil mature across northern Quadrants 41-44, Quadrant 36, 38 and 39.
    - Lower-mid Carboniferous (Visean-Namurian) mudstones and siltstones of the Cleveland Group, over 1 km thick, deposited in dominantly marine environments. Gas mature to overmature in southern Quadrants 41-44 and modelled as having generated oil and gas.
- Potentially widespread reservoir intervals of varying reservoir quality. Favourable intervals include the Upper Devonian sandstone of the Buchan Formation expecially where fractured, channels within the fluvio-deltaic lower-mid Carboniferous (Visean-Namurian) Scremerston, Yoredale and Millstone Grit formations, the laterally extensive, high net:gross Fell Sandstone Formation, and possibly turbidites or shoreface sands within marine mudstones/siltstones in southern Quadrants 41-44 (likely tight gas unless early hydrocarbon charged)
- Widespread opportunities for structural (fault/fold/dip) traps utilising a Silverpit mudstone, or Zechstein evaporite seal as in the Breagh Field. Intraformational Carboniferous seals are documented widely in onshore Carboniferous fields and in some offshore fields and should be further investigated, particularly in mudstone/siltstone-dominated basinal successions with modelled Carboniferous and recent hydrocarbon generation, along with possibilities for stratigraphic traps.
- Basin modelling predicts oil and gas generation at a variety of times (Carboniferous, Mesozoic and Cenozoic dependent on the well) from lower-mid Carbonferous (Visean-Namurian) strata in Quadrants 41-44. In the Forth Approaches, Quadrant 29/North Dogger basins and on the poorly constrained Devonian-Carboniferous Mid North Sea High, oil window maturity levels are modelled at selected wells in a largely gas-prone sequence, though basinwards gas maturity may be achieved. It is recommended that the contribution and volumetrics of relatively thin oil-prone intervals within the Carboniferous succession be further investigated.

Multiple, stacked source, reservoir and seal intervals are commonly interpreted through the kilometres thick Carboniferous and Devonian sequences. Within this, several spatially and geologically distinct Devonian and Carboniferous play systems are described. Lower–mid Carboniferous clastic and basinal plays in Quadrants 41–44 are constrained by the most data and with the highest confidence. At regional scale, a working, generally gas-prone lower–mid Carboniferous petroleum system is present, as proven by the producing Breagh Field.

There are indirect indications (gas chimneys, limited shows, good quality source rocks at the basin margin) of a clastic-dominated lower–mid Carboniferous play present in seismically-mapped basins to the north and east of the Dogger granite block (Quadrants 28, 29, 38, 39). To the north of the Mid North Sea High, oil and gas shows demonstrate the Carboniferous clastic petroleum play of the Forth Approaches basin. Here, maturity levels and timing of migration are key risks.

On the Devonian–Carboniferous Mid North Sea High (Quadrants 34-36), data is very sparse with an attenuated lower Carboniferous and thick upper Devonian sequences interpreted to be present. Some gas prone source rocks are proven but maturity levels are in the early oil window. Gravity and magnetic interpretation points to some possible deeper basins worthy of further investigation. Offshore the Northumberland Trough (southern Quadrant 34), a distinct, potential play containing strata up to Westphalian Coal Measures remains untested.

Upper Devonian–lower Carboniferous sandstones form possible reservoir intervals across much of Quadrants 25–44. The porosity and permeability of these rocks is poorly known and low where measured. In fields that produce from reservoir of this age (Buchan, Auk) fracture permeability is utilised. Little data exists on the source and reservoir potential of mid Devonian limestones and mudstones of the Kyle Group. The few wells that encounter the interval have been drilled on regional highs, and the low source rock quality and porosity values measured are possibly unrepresentative of the unit as a whole.

This regional scale synthesis of Palaeozoic petroleum systems has provided the evidence to encourage more detailed exploration at block and prospect scale in areas such as Quadrants 41-44 and the Quadrant 29–North Dogger basins. Recurring themes which require further investigation include; local variability in source rock, maturity and reservoir quality as controlled by original facies distribution and burial history; productivity of thin oil-prone intervals; intraformational Carboniferous sealing and stratigraphic traps; plus hydrocarbon source typing and migration pathways.

1 Introduction

The 21CXRM Palaeozoic Project aims to stimulate exploration of the Devonian and Carboniferous plays of the Central North Sea - Mid North Sea High, Moray Firth - East Orkney Basin and in the Irish Sea area. The objectives of the project include regional analysis of the plays and building of consistent digital datasets, working collaboratively with the OGA, Oil and Gas UK and industry. The project results are delivered as a series of reports and as digital datasets for each area, Monaghan et al. (2016) provide an overview. This report is the synthesis of project and previous work in the Central North Sea/Mid North Sea High study area.

Outside the Southern North Sea gas fields, Palaeozoic plays are currently described as 'frontier' and risky compared to the Jurassic North Sea petroleum system. Taking a different stance, if instead one considers that:

- coals of the Carboniferous fuelled the Industrial Revolution and the UK for several hundred years;
- James 'Paraffin' Young developed the first hydrocarbon industry from lower Carboniferous oil shales in central Scotland;
- Carboniferous-sourced oil and gas fields are produced onshore;
- Devonian and Carboniferous rocks are well-exposed and well-studied onshore;
- the Carboniferous is currently the focus of unconventional oil and gas exploration;
- the SNS has Carboniferous-sourced, Permian and Westphalian gas fields;

a more positive hydrocarbon potential can be applied to exploration of conventional Palaeozoic plays of the UKCS.

A map of Devonian and lower–mid Carboniferous (Visean and Namurian) oil and gas shows and fields across Quadrants 25–44 highlights a swathe of shows and fields from the Dutch sector, across Quadrants 41-44, onshore to the East Midlands and Cleveland Basin and westwards towards the Carboniferous sourced fields of the East Irish Sea (Figure 1). This report will demonstrate how this petroleum system was sourced from Visean and Namurian clastic-coal and basinal shale sequences, in addition to any long-range migration from Westphalian coals. Key offshore fields in this area are Breagh (Visean), Trent and Cavendish (Namurian).

Onshore, adjacent to the southern and northern margins of the Central North Sea/Mid North Sea High, a working Carboniferous petroleum system has been exploited for many years. The East Midlands oil fields are largely sourced from Namurian basinal shales (Pletsch et al., 2010; Figure 1), are reservoired in Namurian and Westphalian channel sandstones, and have been producing at flat rates for many years. Several Namurian-sourced gas fields occur in the Cleveland Basin (Pletsch et al., 2010), onshore of Quadrant 41.

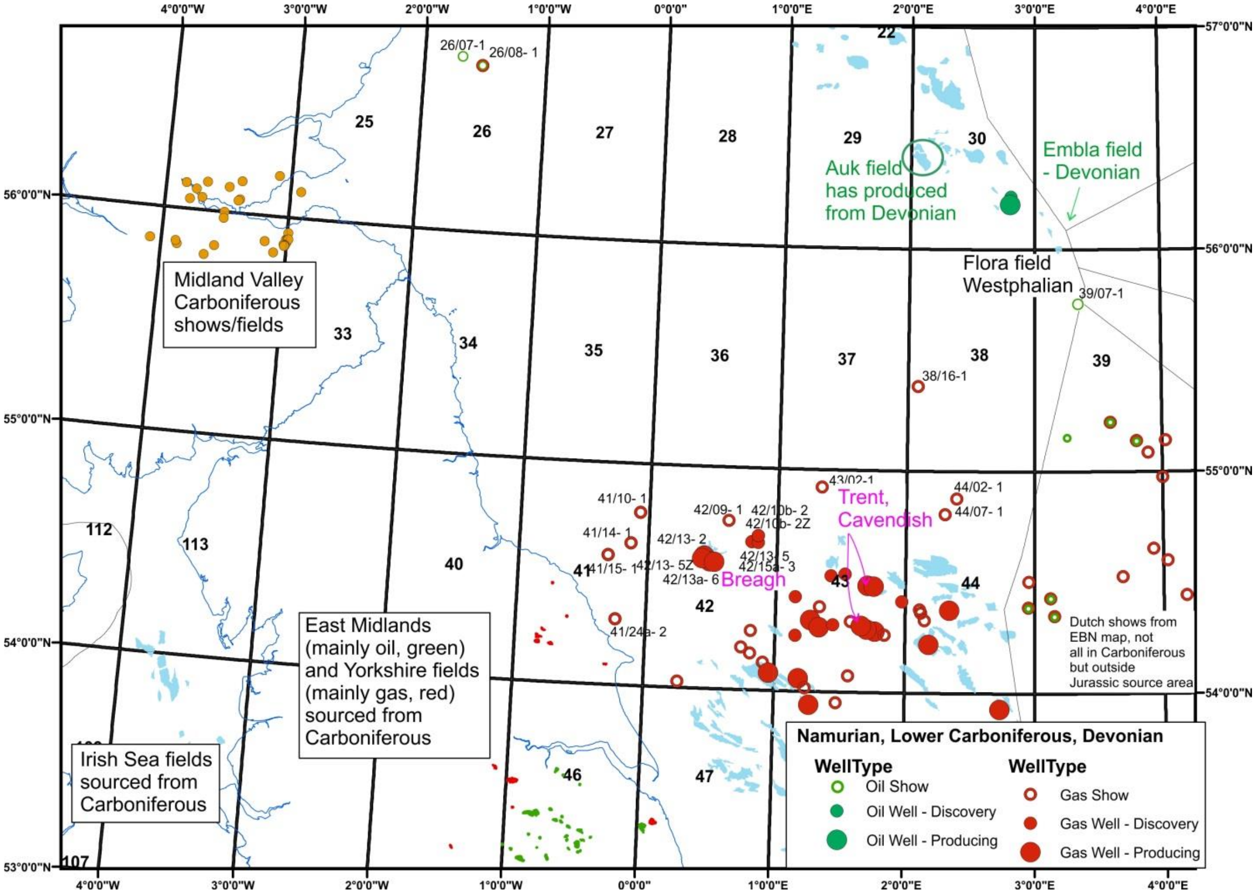


Figure 1 Map of Pre-Westphalian shows, discoveries and fields, Quadrants 25–44

Carboniferous shows in the Forth Approaches plus shows and fields (Midlothian, D'Arcy-Cousland) in the Midland Valley of Scotland (Quads 25-26) attest to a working petroleum system to the north of the Mid North Sea High (Figure 1). Oil and gas production in the Midland Valley of Scotland was sourced from, and trapped in, lower Carboniferous strata (Hallett et al., 1985, Underhill et al., 2008).

The structural fault-block configuration along the Auk-Flora ridge (Quads 30, 39) and in the Norwegian Embla field has allowed Jurassic-sourced migration to reservoirs in upper Devonian-lower Carboniferous or upper Carboniferous sandstone, Permian sandstone and limestone and represents a different petroleum system (e.g. see Glennie et al., 2003).

In recent years, studies of unconventional potential for shale gas/oil, coal bed methane etc. (Jones et al., 2004, Andrews 2013, Monaghan 2014) have highlighted the organic richness of the Carboniferous source rock across central–northern England and the central belt of Scotland, onshore of Quadrants 25–44.

It is notable that the size of conventional onshore Carboniferous traps and fields are smaller than offshore producing fields. For example the Breagh Field has total reserves estimated at 19.8 bcm/699 bcf (DEA Group, 2015; or 16.9 bcm/600 bcf recoverable reserves, Offshore Technology, 2011) whereas the largest onshore gas field, Saltfleetby, has ultimately recoverable reserves of 2.08 bcm/73 bcf (Breunese et al., 2010; Hodge, 2003). The depositional facies, burial history and structural configuration of the Carboniferous are more complex than many of the younger UKCS petroleum plays. However many of these challenges have been successfully overcome in the Southern North Sea Westphalian and Permian gas play.

The Breagh Field and other discoveries (e.g. Crosgan 42/10b- 2; Figure 1) have proven a working Carboniferous play at such distances from the Westphalian-sourced gas fields of the Southern North Sea that long range migration of Westphalian-sourced gas is questionable. Gerling et al. (1999) highlighted the likely contribution of a mature marine source in addition to

Westphalian Coal Measures to gas fields of the Southern North Sea. Dolan and Associates (1994) recognised the potential of coal-derived gas outside the Westphalian of the Southern North Sea. Using a comprehensive well database they estimated about 550 tcf of gas may have migrated from the Firth Coal Formation (Quadrants 14, 15, 26) to conventional reservoirs and about 23 tcf may have been liberated from the Scremerston Formation (Quadrants 42, 43, 44; in the relatively restricted area it was identified at that time). Namurian coals were also identified as gas sources (Dolan and Associates, 1994).

The synthesis work below is a *regional scale* synthesis of 21CXRM Palaeozoic Project, together with previous published work. The aim is to provide a consistent set of data and interpretations as a framework to support exploration at block and prospect level.

2 Overview of Palaeozoic petroleum systems in Quadrants 25–44: stacked heterolithic plays

Six Palaeozoic petroleum systems can be defined within Quadrants 25–44 (Figure 2).

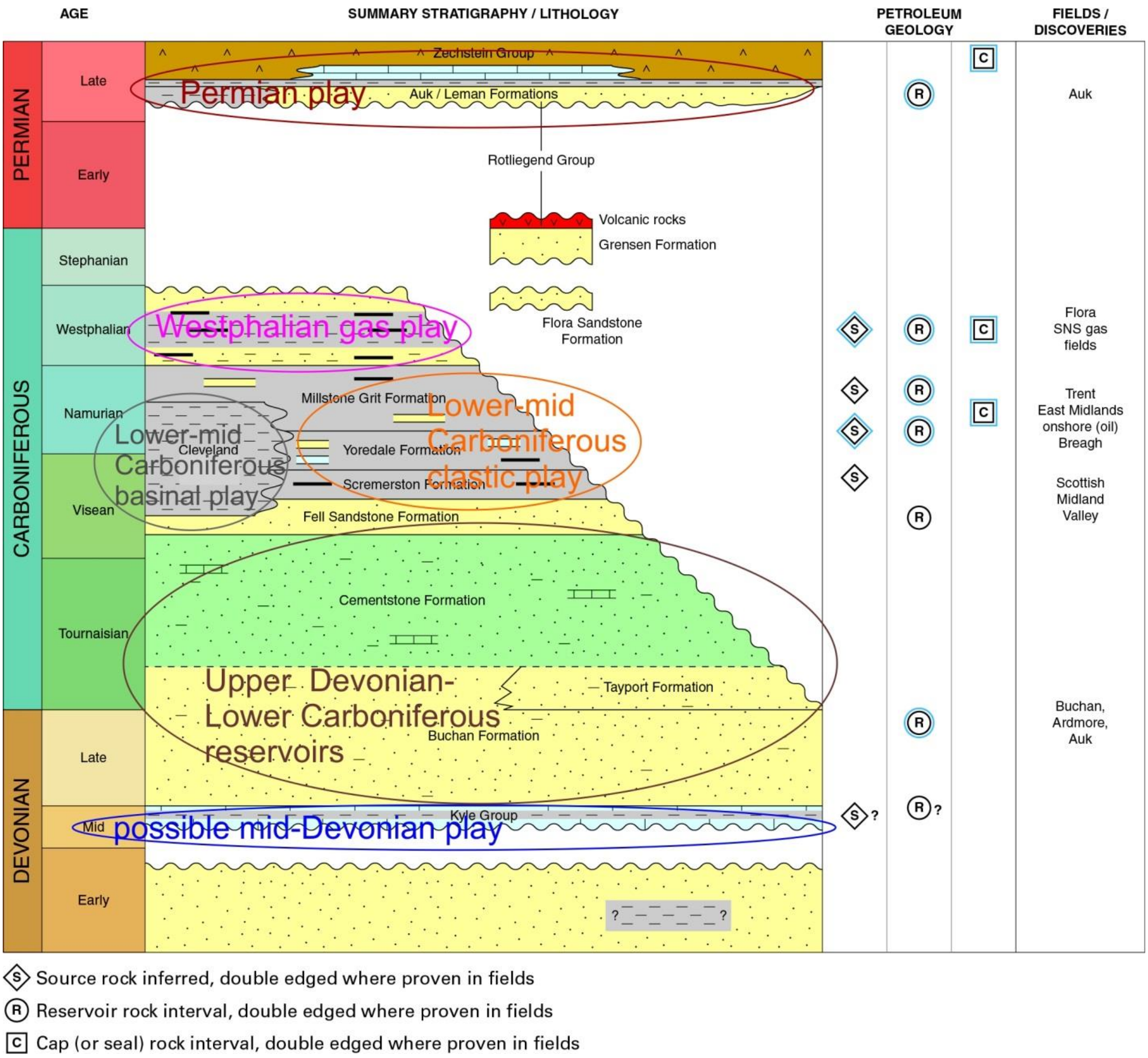


Figure 2 Simplified overview of late Palaeozoic stratigraphy and plays

The spatial extent of the plays is controlled by both depositional extent and facies variations (e.g. lower–mid Carboniferous delta-top clastic play to siltstone- and mudstone-dominated basinal play) and erosion at the latest Carboniferous-early Permian Variscan Unconformity (Figure 3). Facies variations and stratigraphical nomenclature are discussed in detail in Kearsey et al. (this study).

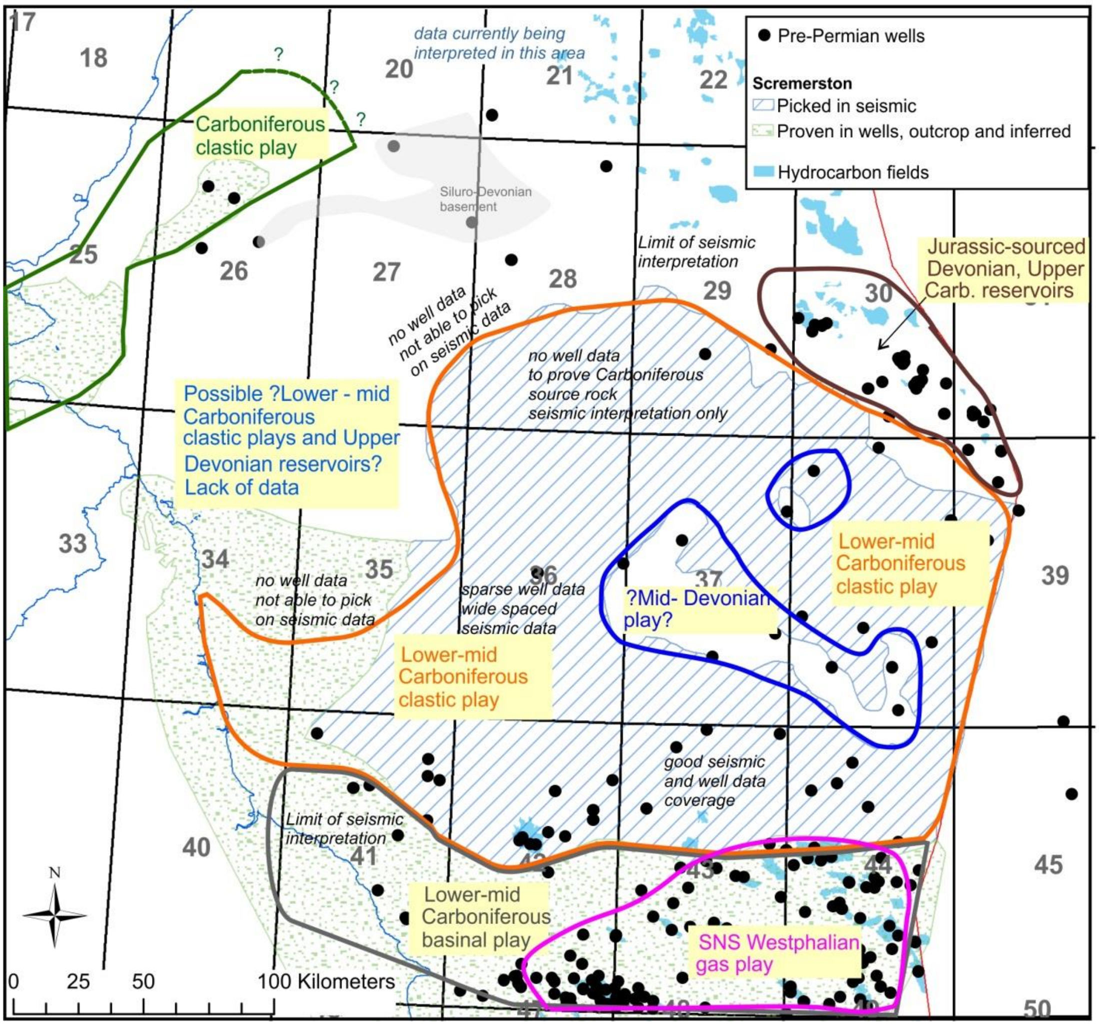


Figure 3 Approximate extent of uppermost Devonian and Carboniferous play systems, with the extent of Scremerston and time equivalent formations (potential source and reservoir) shown in the background for reference. Note that the possible Mid Devonian play and upper Devonian-lower Carboniferous reservoirs could be extensive underneath the lower–mid Carboniferous plays.

An overview play cartoon (Figure 4) highlights the vertically stacked and laterally equivalent petroleum systems. Structural and dip traps of faulted/folded Devonian and Carboniferous strata against the base Permian unconformity (BPU) and seal (Zechstein evaporites) are the primary trap/seal mechanism. High quality Permian reservoirs (Auk, Leman sandstones) are also located beneath the Zechstein seal in some parts of the study area. Detailed study of the Permian succession was out with the scope of the current work. Intraformational Carboniferous traps and seals could, if effective, be extremely important.

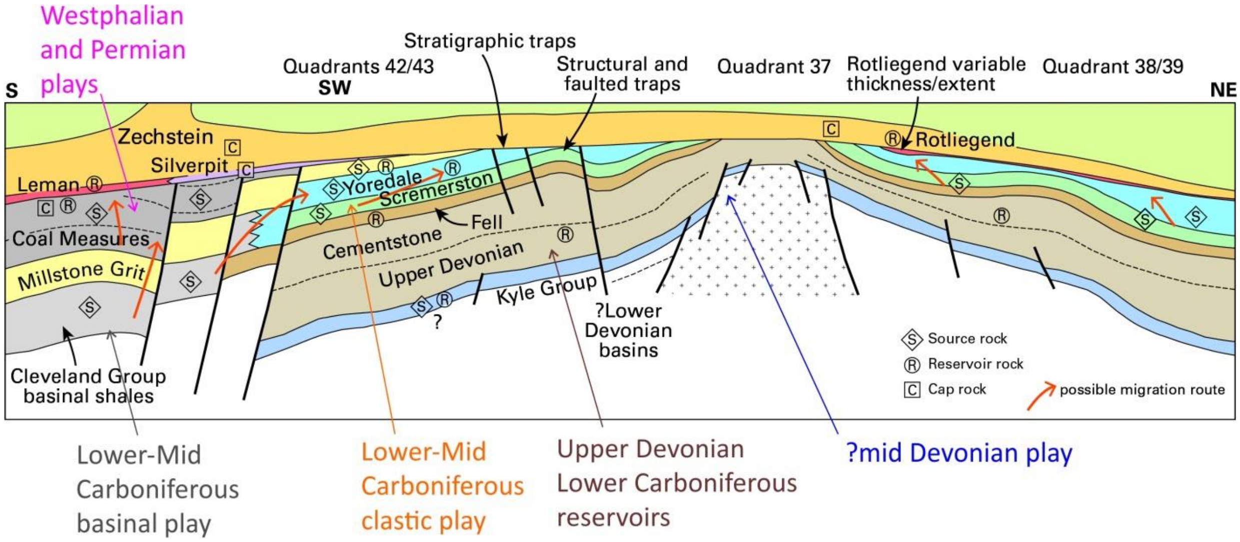


Figure 4 Overview Palaeozoic play cartoon, Quadrants 38-43

In this study, well and seismic interpretations have identified a far greater extent of lower–mid Carboniferous strata than current published limits and in a better understanding of Palaeozoic structure (blocks, shelves and basins) over a large part of the 'Mid North Sea High' (Figures 5, 6).

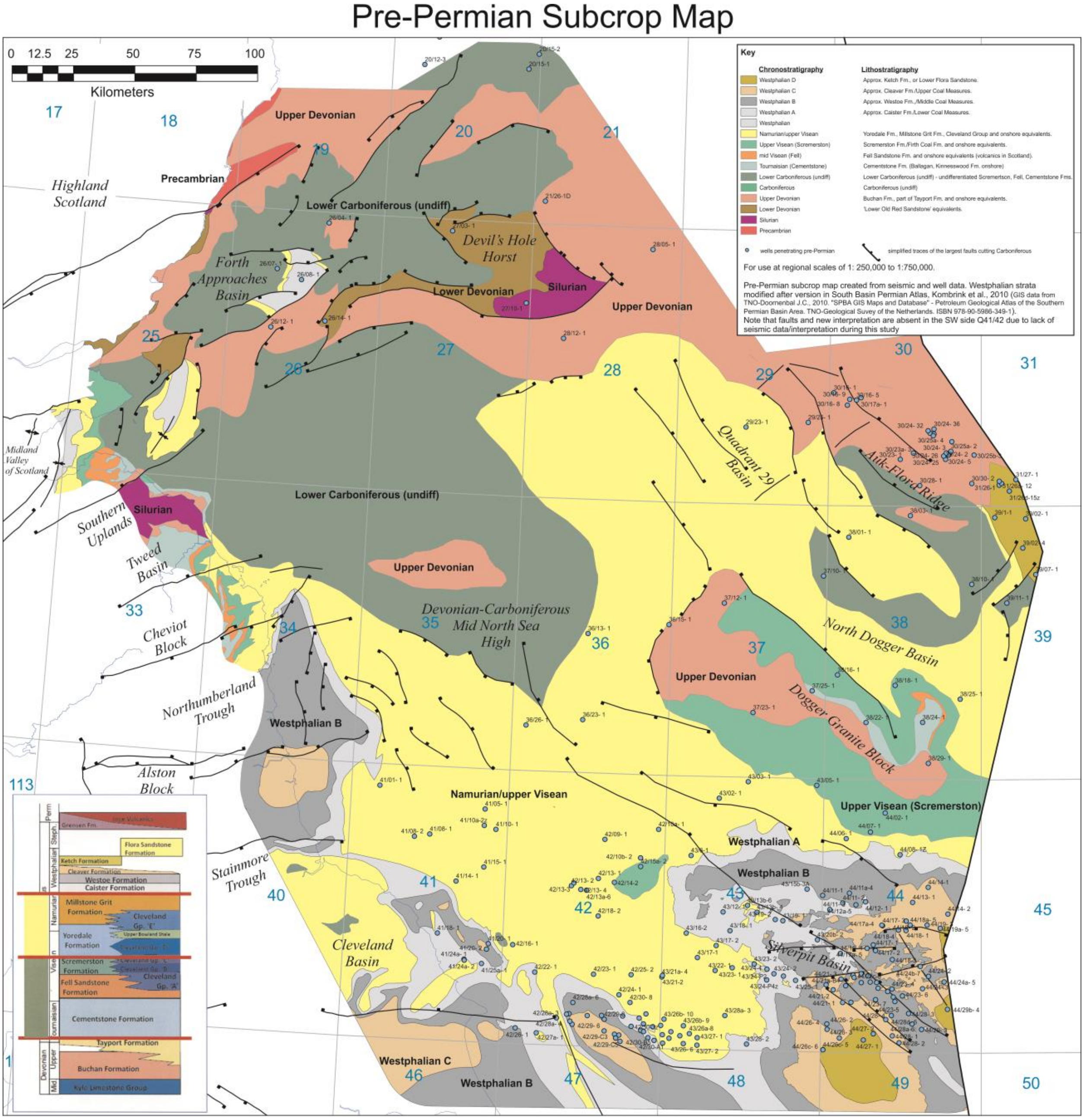


Figure 5 Pre-Permian subcrop map. Westphalian strata in Quads 40-49 modified after Kombrink et al., 2010. The stratigraphic column (bottom right) shows the stratigraphic equivalence of the yellow (Namurian/upper Visean) and green (lower Carboniferous undifferentiated) mapped units.

The 'Mid North Sea High', a term used for the division of the Southern and Northern Permian basins, is a complete misnomer for the Devonian-Carboniferous succession. The area is crossed by Devonian-Carboniferous basins commonly at 3-4 km depth and up to 6 km in thickness. (Figures 6 and 30-33). Several kilometres of heterolithic sandstones, siltstones, limestones, coals and mudstones provide a stacked source, reservoir and possibly intra-formational seals within the Palaeozoic basin fill. Granite-cored highs and terraces/slopes are also observed across the region, which is interpreted to have developed in response to partitioned extension, transtension and transpression acting on inherited basement structural trends (Leslie et al., this study). Based on the current dataset, the area which does appear to have been the Devonian-Carboniferous 'Mid North Sea High' is within orange area of Figure 7, though the 2015 Government-funded seismic data may reveal previously unimaged basins across this area, as suggested by the gravity modelling (Kimbell et al., this study).

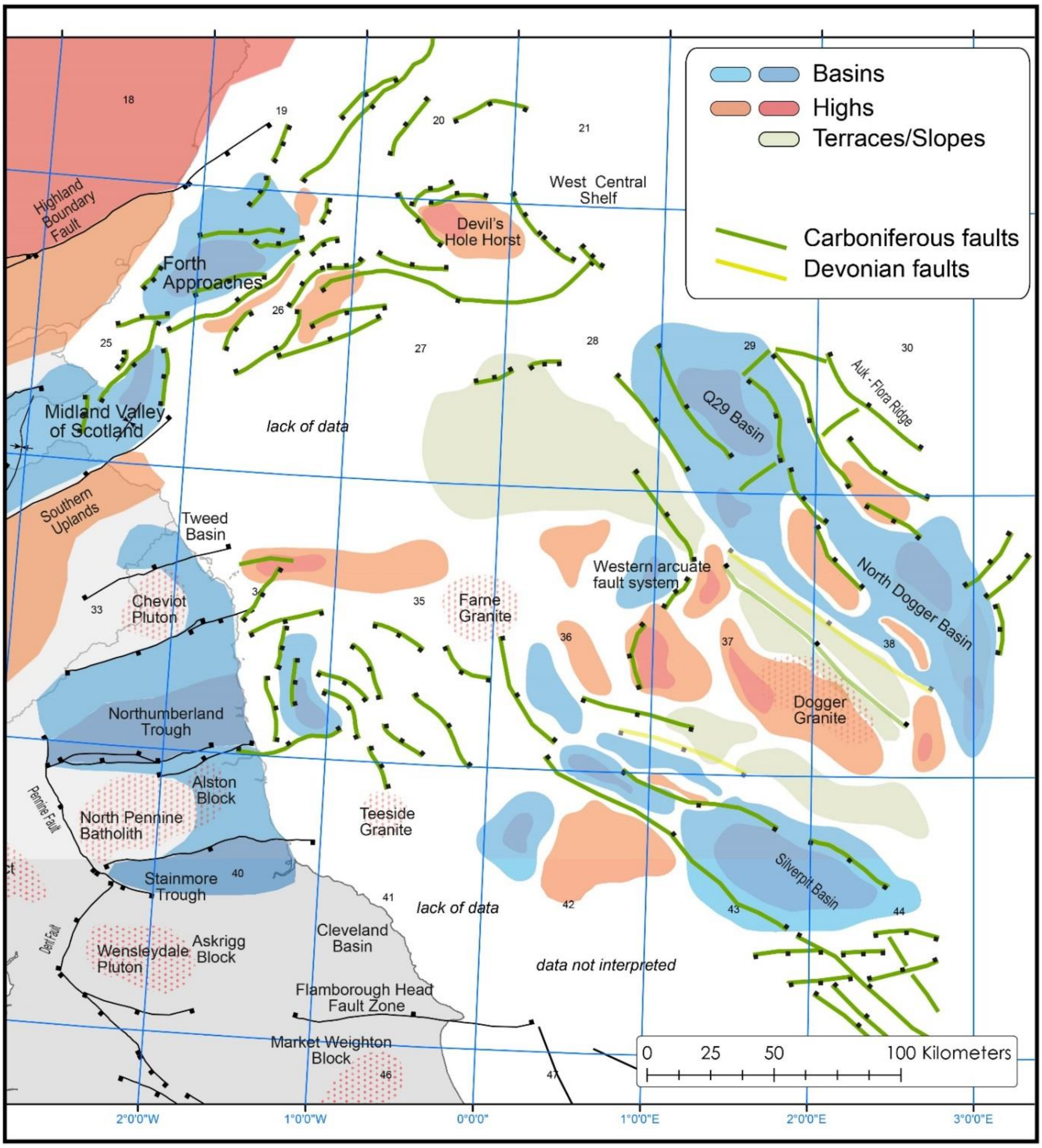


Figure 6 Structural summary map of Devonian-Carboniferous basins and highs across the MNSH/CNS study area

The definition of Devonian-Carboniferous basins together with variations in stratigraphy and data density/quality has facilitated subdivision of the sub-areas shown on Figure 7. The sub-areas are used in the description of the petroleum systems below.

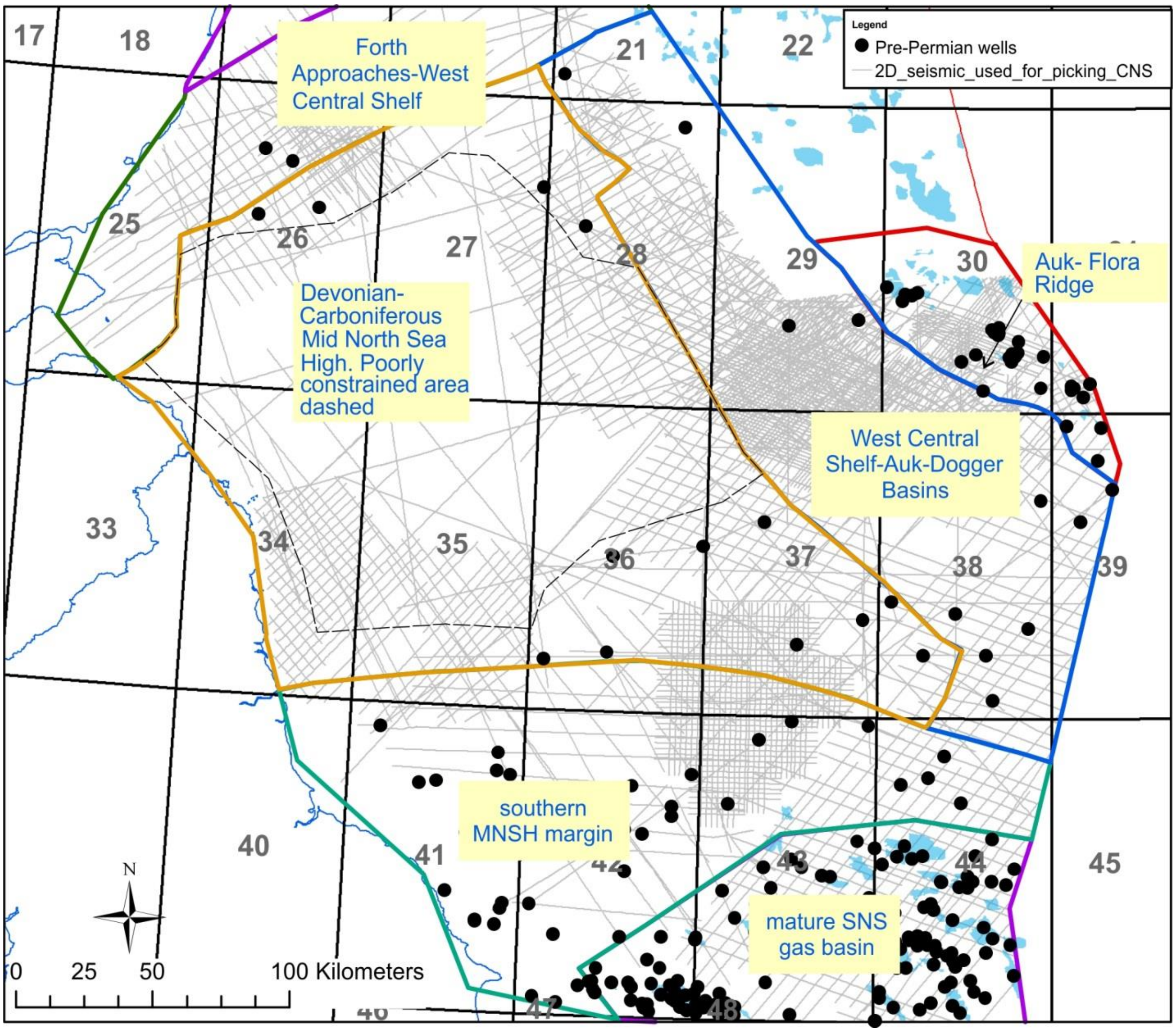


Figure 7 Subdivision of Quadrants 25–44 to geological/petroleum system/data-defined sub-areas as described in the text. MNSH=Mid North Sea High. 2D seismic datasets and pre-Permian wells are also shown, 3D seismic data used in Quadrants 28, 29, 30, northern 37-39 and Quadrant 42 is not shown. The Devonian-Carboniferous Mid North Sea High is currently defined in the orange area, particularly in the 'poorly constrained by data' part.

2.1.1 Interpretational confidence

It is clear from the seismic and well map shown on Figure 7 that data density is extremely variable across the study area. The vintage and quality of pre-Permian datasets is also variable, resulting varying interpretational confidence across the areas studied. The least data and lowest confidence is over the dashed area of the Mid North Sea High on Figure 7, the most data and highest confidence is for the southern MNSH margin. Annotations and labels have been used on figures to describe and depict confidence in interpretations made during this study.

2.2 SOURCE ROCK, TYPING, MATURITY AND MIGRATION OVERVIEW

One of the key risks to Palaeozoic plays is the presence, quality, maturity and timing of maturation of source rock intervals. This section gives a regional overview of various source rock indicators. Compilation of Rock-Eval source rock geochemical data for Quadrants 25–44 (selected wells in Quadrants 43 and 44) revealed a large dataset of variable vintage, quality and well location (Vane et al., this study). 150 new samples were analysed for this project to supplement regional coverage. Released data is available as an Excel spreadsheet to enable further analysis.

Over 1800 Carboniferous core and cuttings samples highlight the organic richness of this interval with a significant proportion falling within 2-9% TOC (good source rocks are >2% total organic carbon, TOC). There are a significant number of carbonaceous mudstones and coals between 20-90% TOC (Figure 8). In contrast, Devonian age samples generally have TOC <2% (Figure 8; less than 200 Devonian samples).

To further assess source rock quality, an alternative regional petrophysical screening of TOC contents was undertaken over a more extensive depth range than geochemical sampling (Gent, this study). Coals are excluded from the calculation as the method is not accurate for coals, resulting in an underestimate of the source rock potential. However, this balances the positive bias from the geologist choosing the blackest mudstones for organic geochemistry sample analysis. The petrophysical screening work showed encouraging results for organic rich shales within the Cleveland Group, Millstone Grit, Yoredale and Scremerston formations (Gent, this study), which are discussed in detail in the sections below.

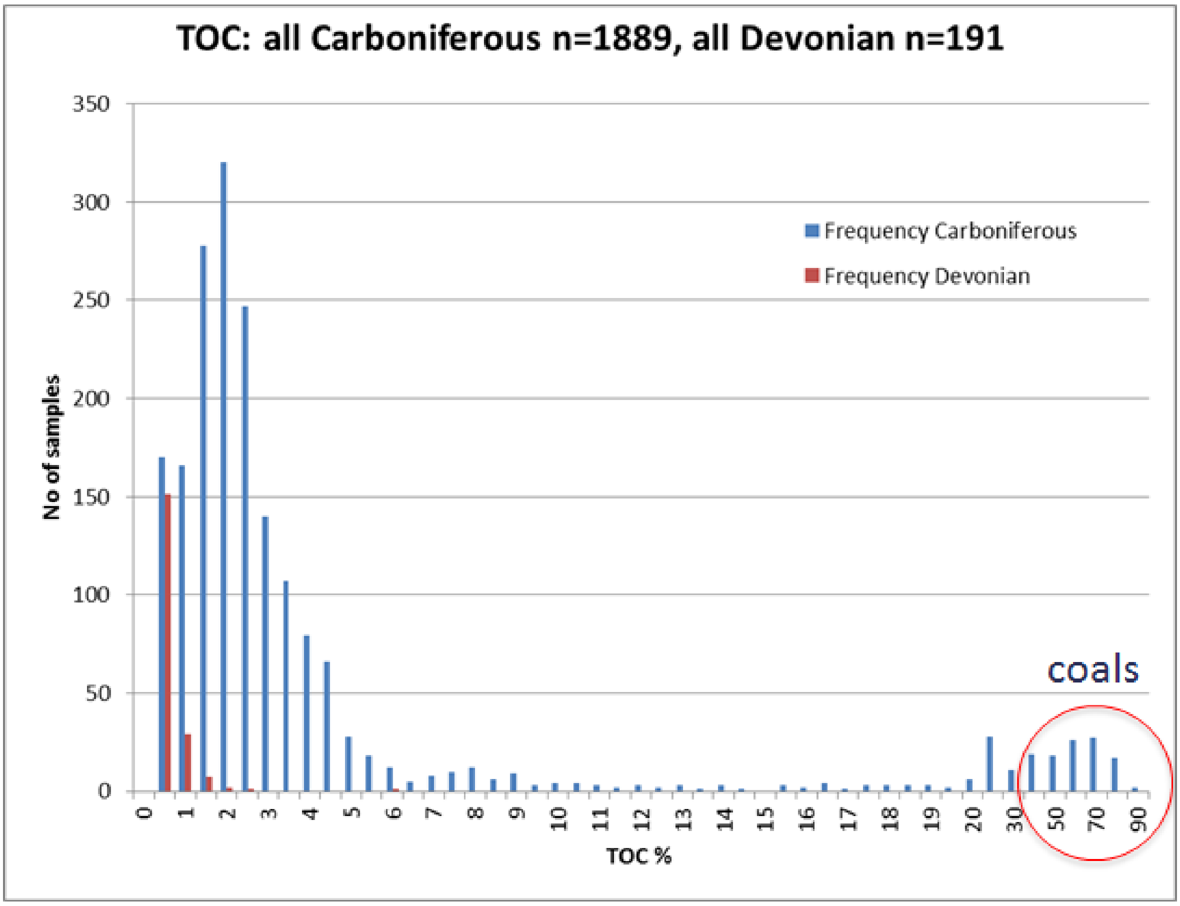


Figure 8 Histogram of measured total organic carbon contents (TOC) on Carboniferous and Devonian samples from Quadrants 25–44 core and cuttings samples.

A Van Krevelen plot highlights a range of kerogen types I, II, III and IV as would be expected from the range of Devonian and Carboniferous sedimentary depositional environments (Figure 9). Type III kerogens are perhaps the most prevalent, with many of the analyses plotting in the bottom left-hand corner, indicative of mature samples.

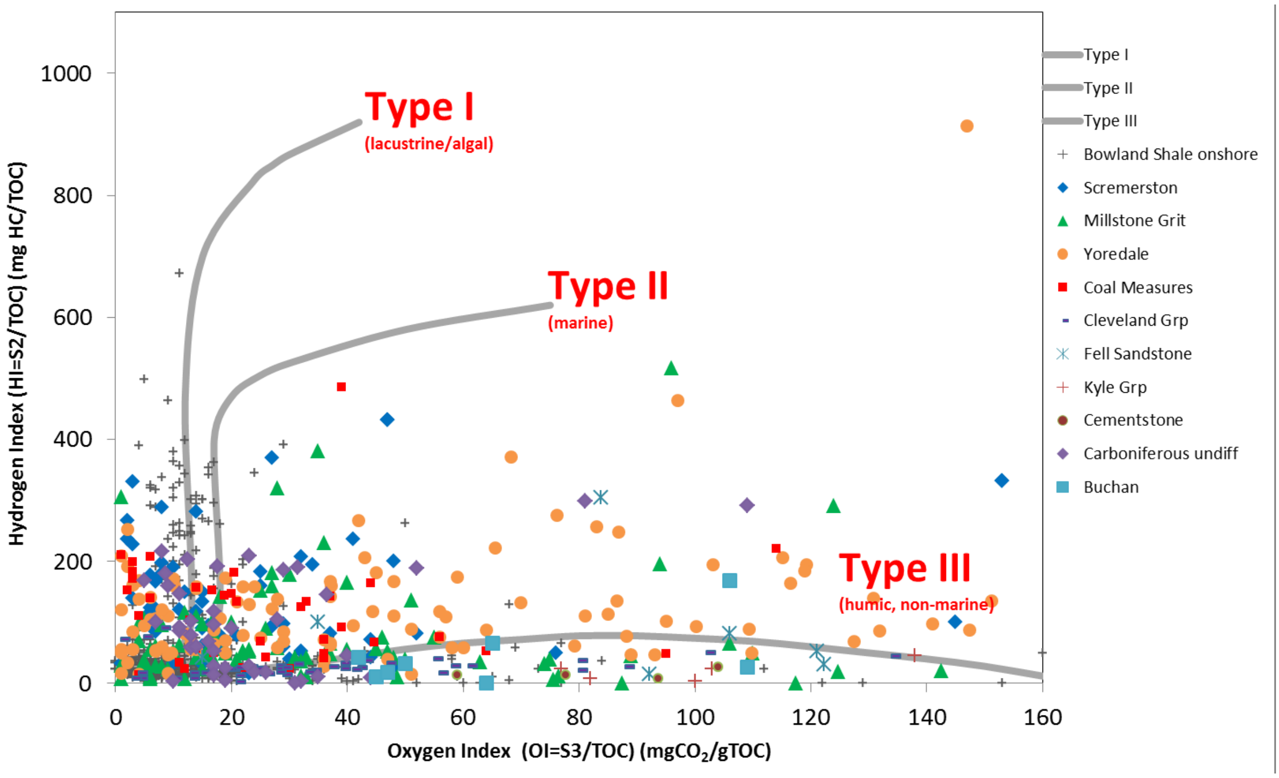


Figure 9 Van Krevelen plot giving an overview of kerogen types and maturity for the Carboniferous and Devonian of the MNSH/CNS, together with the onshore Bowland Shale data from Andrews (2013) for comparison.

A similar picture of mixed kerogen types with dominant Type III (humic, vitrinite) kerogens is observed from a literature review of visually or geochemically analysed kerogen (Figure 10).

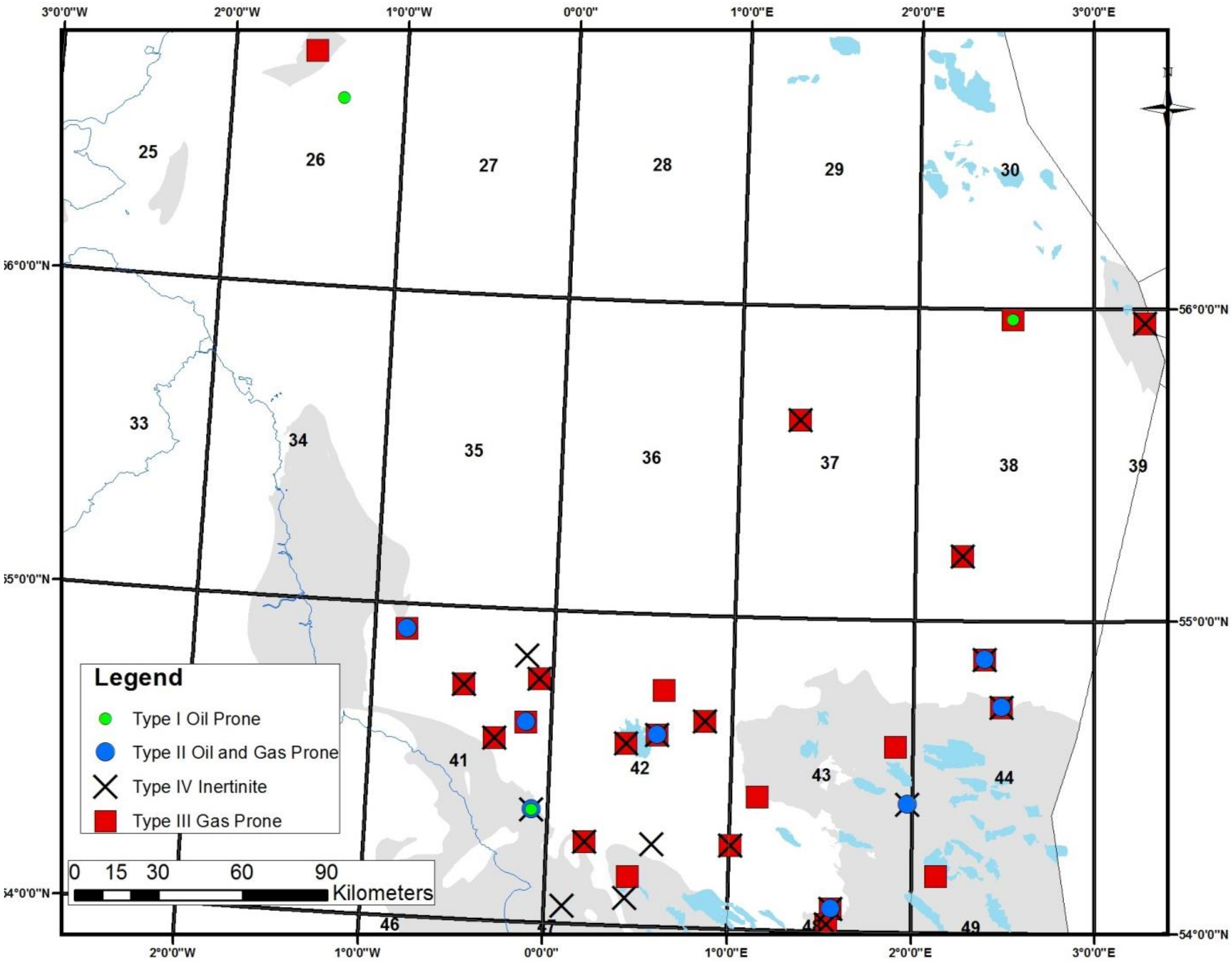


Figure 10 Plot of wells with >30% of the kerogen type shown, from visual or geochemical evaluation extracted from a literature review of well reports for Devonian and Carboniferous core or cuttings samples. Extent of Westphalian Coal Measures strata in grey, fields in pale blue.

A non-marine Carboniferous source is also the most common geochemically-typed source in analyses of migrated hydrocarbons, shows and fluid inclusions from a literature review (Figure 11).

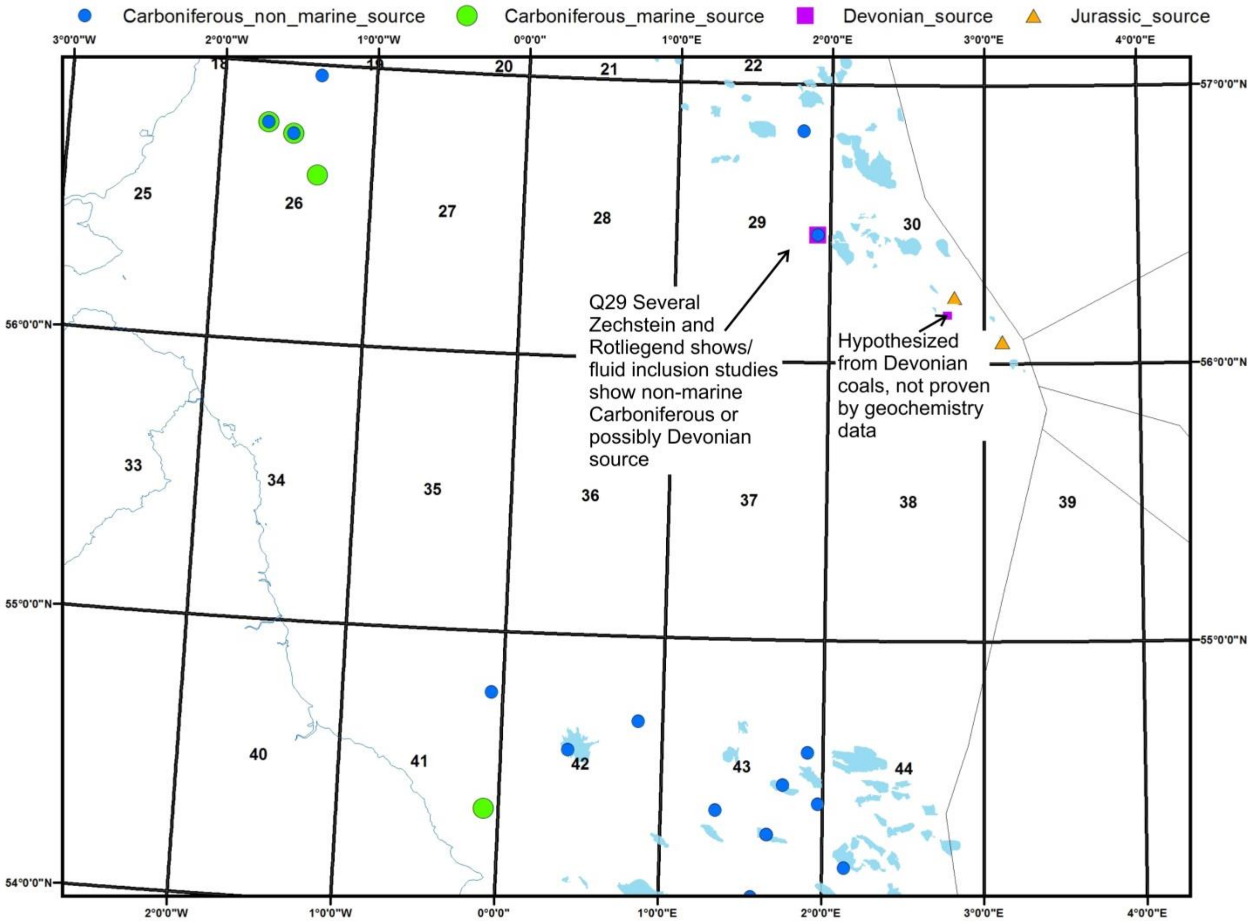


Figure 11 Plot of migrated hydrocarbons, shows and fluid inclusions geochemically analysed for source rock type, from a literature review of well and other donated reports.

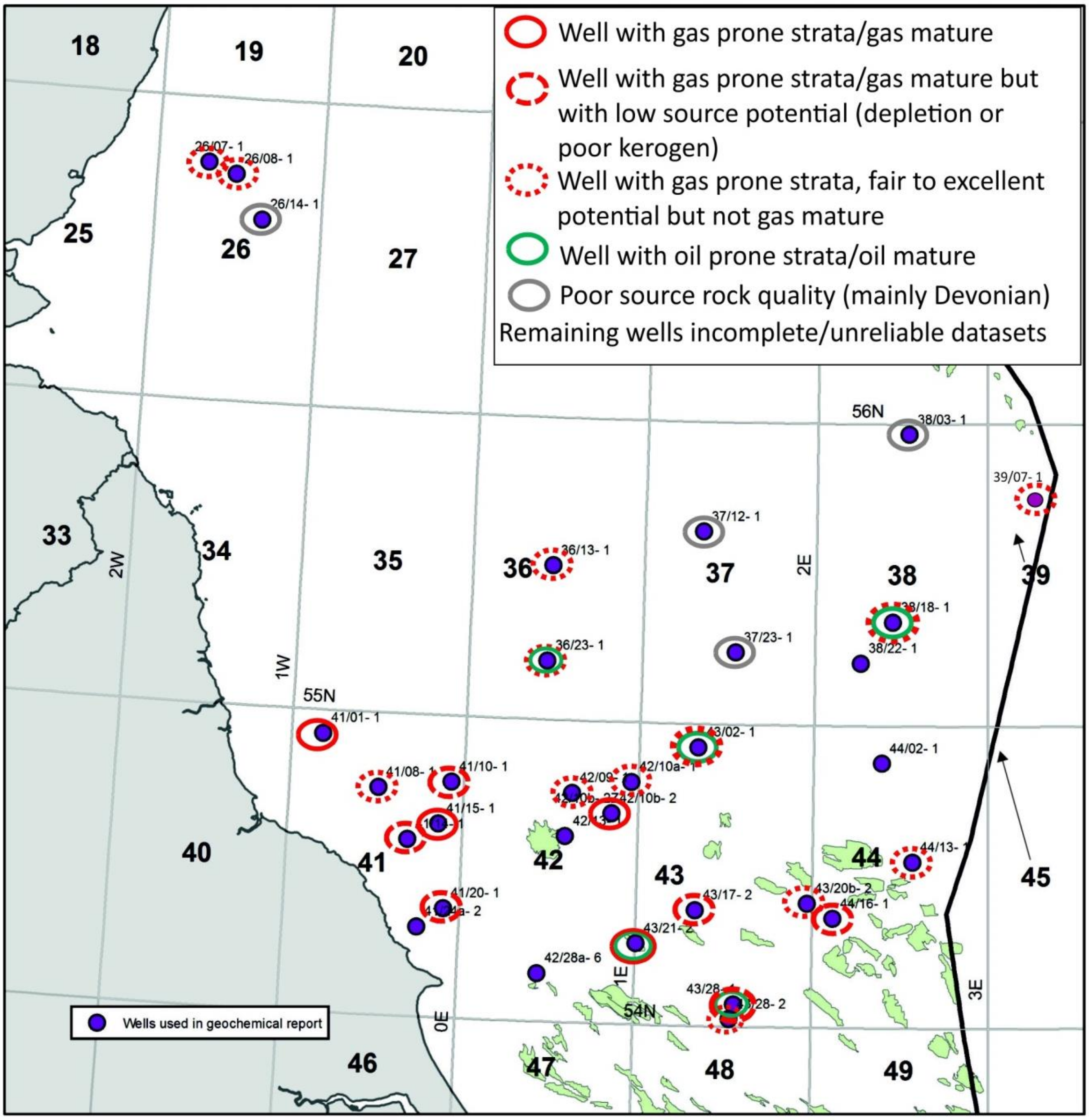


Figure 12 Summary map of source rock geochemical screening analysis for the Devonian-Carboniferous interval in the wells shown.

Source rock (Rock-Eval) geochemical data was screened per well using standard criteria to give an overview of the source rock quality, type (oil or gas prone) and maturity (Vane et al., this study). The majority of the wells examined were gas prone (Figure 12). The source rock quality varied from poor to excellent, with the Scremerston, Yoredale, Cleveland, Millstone Grit and time-equivalent units all exhibiting source rock potential in addition to Coal Measures strata. Maturity levels vary from immature to fully gas mature. In addition to some gas-prone, gas mature wells there is evidence for both a) good quality source rocks that are immature/oil mature but offer potential if similar strata were more deeply buried in adjacent basins (largely in northern Quadrants) and b) gas mature source rocks that may have generated some hydrocarbon and may now be depleted/overmature (largely in Quadrant 41 and southernmost Quadrants; Figure 12). Further details are given in the petroleum system descriptions below.

In very simplistic and generalised terms, in Quadrants 41–44, wells in which the top Scremerston Formation and equivalents are buried more deeply than 2.5 – 3.5 km at the current day appear to have entered the gas window. However a complex burial/uplift and heat-flow history result in quite different timing and generation of hydrocarbons from wells buried at similar depths (basin modelling work Vincent, this study, Leslie et al., this study). Only one well (43/17- 2) is modelled as being at its deepest burial at present day (Vincent, this study).

Previous thermal basin modelling studies of the Devonian-Carboniferous have also highlighted variability in the timing and predicted oil/gas generation, largely due to spatial variability in depositional lithofacies and the timing and amount of uplift/burial (e.g. Collinson et al.; 1995 Quadrants 41-43; Hay et al., 2005 Quadrant 29; Granby & TGS Nopec 2010, Quadrant 26).

In this study, several wells on the southern side of the Mid North Sea High (Quadrants 41-43) are modelled in 1D to have Cenozoic oil and gas generation/migration, favourable for current day hydrocarbon accumulations (Vincent, this study). Some wells in Quadrant 41 show evidence of late Carboniferous hydrocarbon generation and possibly depletion, before current traps existed, with remaining generation occurring in Mesozoic-Cenozoic times (Vincent, this study). In the Forth Approaches well studied, late oil maturity was reached in the Scremerston/Firth Coal interval in the Cenozoic but the interval is interpreted as largely gas prone. More deeply buried parts of the basin may have reached gas maturity but the volume is likely to have been small. Wells on the Mid North Sea High (Quadrant 36) are within the early oil window in a largely gas prone succession (Vincent, this study). Of particular relevance to the Forth Approaches, Mid North Sea High and Quadrant 29-Dogger Basin areas, where the current dataset is indicative of oil window maturity levels, the generative capacity of relatively thin oil prone intervals merits further study.

Maturity and migration modelling was also performed in 3D using the 5 km resolution seismic depth grids (base Zechstein, top Scremerston, top Fell Sandstone, top Cementstone, top Kyle Group: note grids were not interpreted for source rocks within the Yoredale Fm, Cleveland Group etc). Oil and gas generation/expulsion from the Scremerston Formation is modelled in central parts of Quadrants 42-44 (Figures 13, 14). However the migration and accumulation modelling performed was deemed to be questionable due to the limited extent and 5km (i.e. much smoothed) resolution of seismic depth grids resulting in misleading long range migration pathways and lack of coincidence with proven fields/discoveries. The migration pathway and accumulation results have not been included in the project results, instead a generalised indication of modelled migration directions is given (Figures 13, 14)

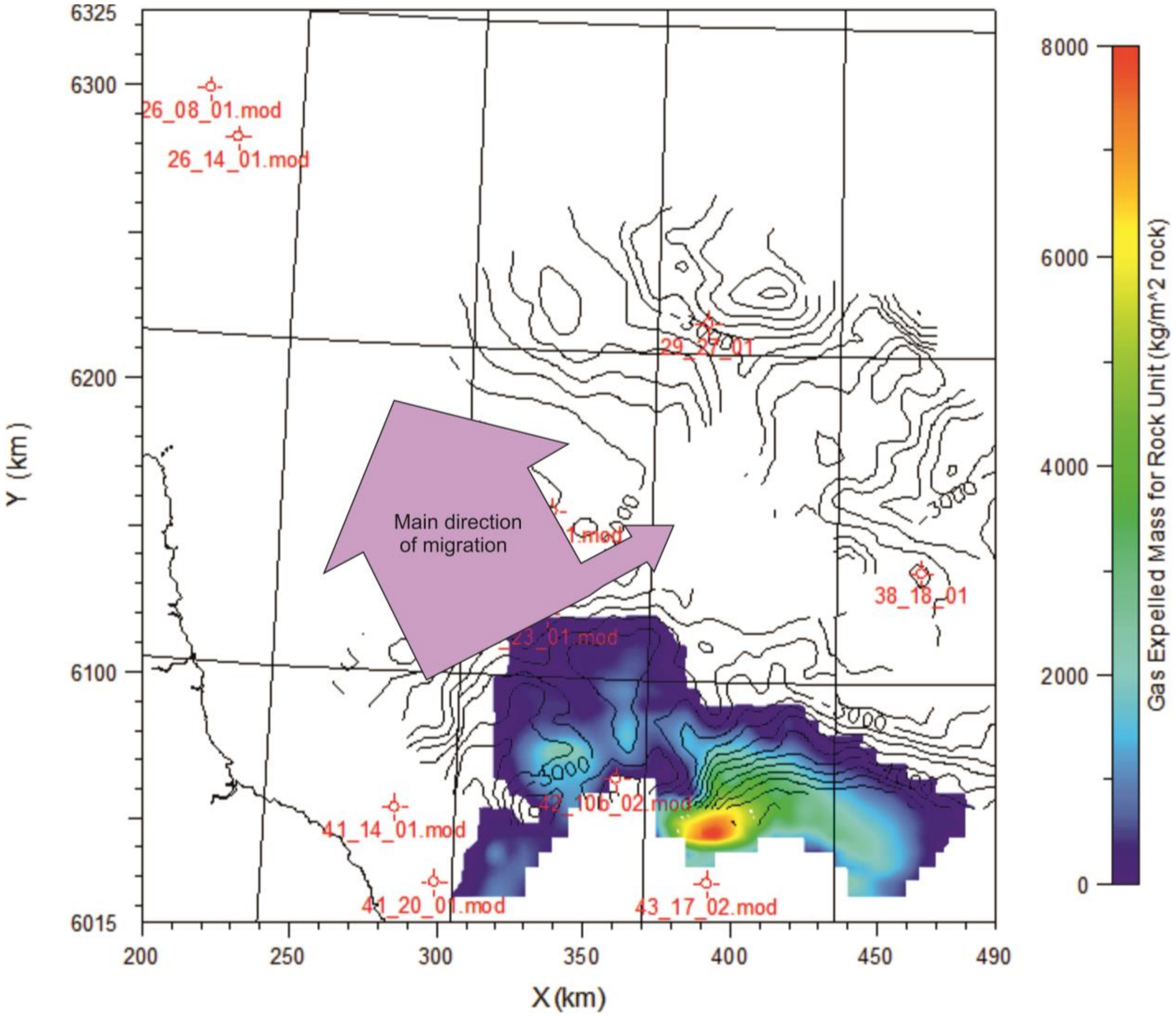


Figure 13 Model of gas expelled from the Scremerston Formation (total mass per rock unit), (model time is close to present day). Wells 43/17-02 and 41/20-01 do not penetrate to the Scremerston Formation, but based on maturity of younger Carboniferous rocks, it would be expected that the Scremerston in this region reached the oil and gas maturity windows over the geological history of this region. Generalised directions of migration are shown. Contour lines are depth to top Scremerston Formation in metres.

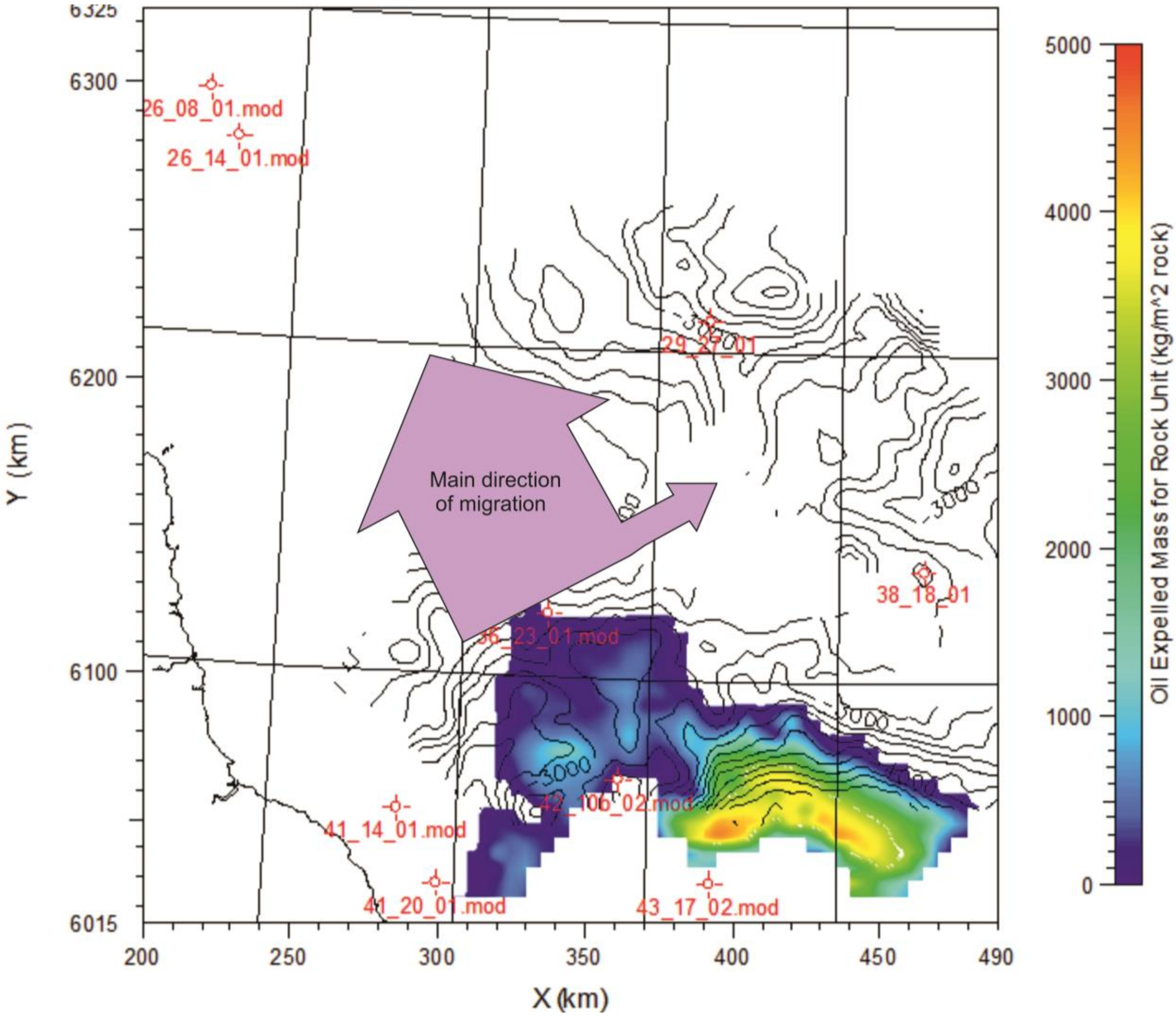


Figure 14 Oil expelled from the Scremerston Formation (total mass per rock unit) at time close to present day. Wells 43/17-02 and 41/20-01 do not penetrate to the Scremerston Formation, but based on maturity of younger Carboniferous rocks, it would be expected that the Scremerston in this region reached the oil and gas maturity windows over the geological history of this region. Generalised directions of migration are shown. Contour lines are depth to top Scremerston Formation in metres.

The main message from the migration maps is of oil and gas generation in the southern, basinal play and up-dip migration to regional highs. Similar migration pathways in Quadrants 41-43 were predicted by Collinson et al. (1995) into up-dip clastic reservoirs.

In summary, a regional overview of Carboniferous source rocks and generated hydrocarbons shows that Quadrants 41–44 contain good quality source rocks that are gas mature and this area is modelled as being a generative centre (kitchen) in Cenozoic times. Carboniferous wells that have sampled less deeply buried strata on the margins of the North Dogger Basin or on the Mid North Sea High area of Quadrant 36 have the source rock potential for gas and some oil generation, should similar rocks be buried more deeply in the adjacent basins.

2.3 RESERVOIR OVERVIEW

Reservoir rock extent and quality is highly variable in Devonian and Carboniferous sequences depending on depositional facies, burial and diagenetic history. The reservoir interval in the Breagh Field comprises lower Carboniferous channel sandstones within the Yoredale Formation (RWE Dea 2011a; Symonds et al., 2015). In Quadrant 43, Millstone Grit Formation sandstones are reservoirs in the Trent and Cavendish fields. In the Argyll field, the upper Devonian reservoir was of braided fluvial sandstones and conglomerates with fracturing enhancing the reservoir properties (Marshall and Hewett, 2003).

In this study, generalised intervals have been identified as potential reservoir rocks from their higher net to gross, limited measured porosity and permeability data, continuous petrophysical interpretation, and where proven in existing fields and discoveries. To give a regional picture, the approach taken was of regional screening using petrophysical techniques calibrated by the small depth ranges with measured core data (Hannis, this study). Core measurements from wells not used in the petrophysical study have not been systematically evaluated. Some show variability from the petrophysical results (e.g. the Fell Sandstone in 43/02- 1 has an average porosity of 13 % and average horizontal permeability of 18 mD). More detailed work is now required to evaluate the most promising reservoir units integrated with depositional history, burial history and diagenesis – all these factors vary between wells.

Table 1 provides a summary of measured porosity and permeability in wells interpreted in the petrophysical work (Hannis, this study) which illustrates the variable porosity and generally poor permeabilities, but with some wells exhibiting good permeabilities. For example, the high poro-perm of the Scremerston/Firth Coal Formation core samples in 26/07- 1 were from cores taken at 5-15 m thick sand bodies.

						Core porosity (fraction)			Permeability (Kair, mD)		
Well	**Formation**	**Number of points**	**Core type**	**Depth of top core measurement (m)**	**Depth of bottom core measurement**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**
43/21- 2	Millstone Grit	8	*Rotary side wall core*	3317.0	4057.0	0.09	0.04	0.13	0.07	0.01	0.13
	Cleveland Group E	1		4120.0	4120.0	0.02	0.02	0.02	0.01	0.01	0.01
	Upper Bowland Shale	8		4664.5	4723.0	0.02	0.01	0.02	0.01	0	0.01
	Cleveland Group D	1		4773.5	4773.5	0.01	0.01	0.01	0	0	0
41/01- 1	Yoredale	30	*Conventional core*	906.2	933.0	0.1	0.04	0.14	1.51	0.02	7.09
42/10a- 1	Yoredale	38		2566.3	2992.8	0.13	0.01	0.2	39.2	0.1	795
26/07- 1	Scremerston	65		1481.8	1557.5	0.18	0.04	0.26	295	0.12	1460
42/15a- 2	Scremerston	281		2380.0	2488.0	0.06	0	0.18	0.66	0	16
41/01- 1	Fell	37		1953.5	1979.7	0.04	0.01	0.07	0.16	0	4.11
37/12- 1	Buchan	5		2533.5	2545.7	0.06	0.05	0.06	0.02	0	0.1
	Kyle	6		2787.7	2802.9	0.03	0.03	0.05	0.01	0	0.02

Table 1 Summary of digitised core porosity-permeability measurement data by formation, for the wells studied in the petrophysical study Hannis (this study). Porosity-permeability data has only been evaluated for wells included in the petrophysical study. Other core measurements have been compiled, but not systematically evaluated, and show variability from the results above.

Higher values of porosity generally correlate with high values of permeability (Figure 15).

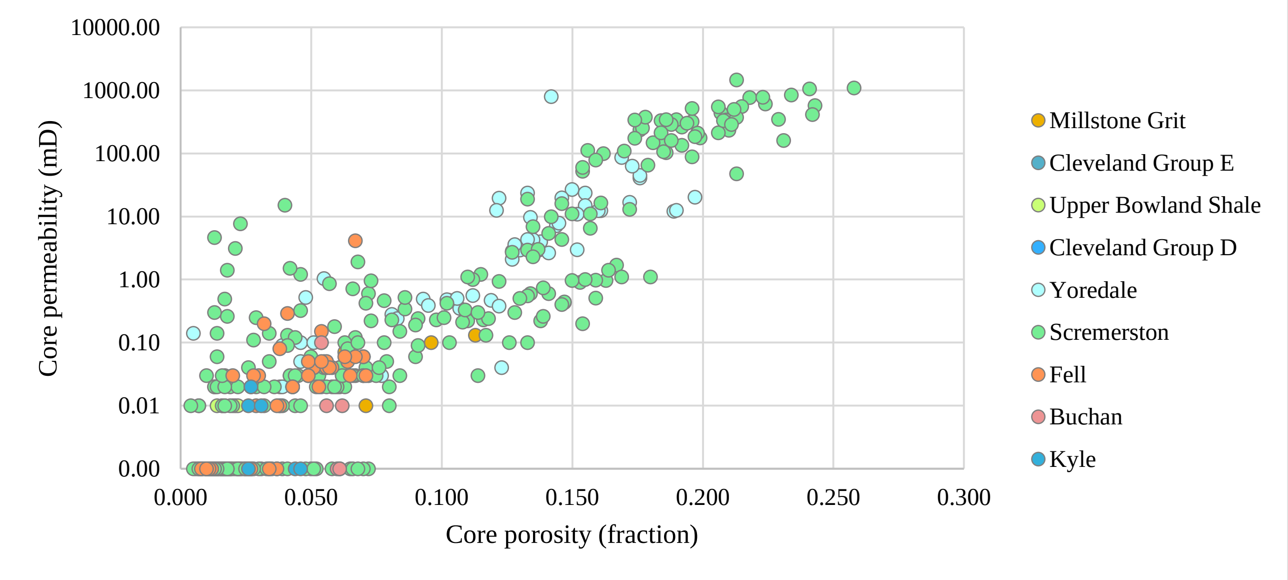


Figure 15 Cross plot of core porosity and permeability measurement data by formation for the wells examined in the petrophysical study (Hannis, 2015).

A simple depth versus porosity function is not demonstrated in the measured and petrophysical porosity due to the restricted depth range of samples from different formations, combined with multiple phases of burial and uplift (Figure 16a, b). The maximum measured porosity generally decreases with increasing present day depth, though there is a great deal of variability especially for petrophysical PHIE calculations that represent all lithologies with clay volume < 50%, as opposed to core measured values that are likely to have sampled the best, clean sandstones (Figure 16a, b). Future work should examine porosity-permeability values against maxium burial depths for all available core data.

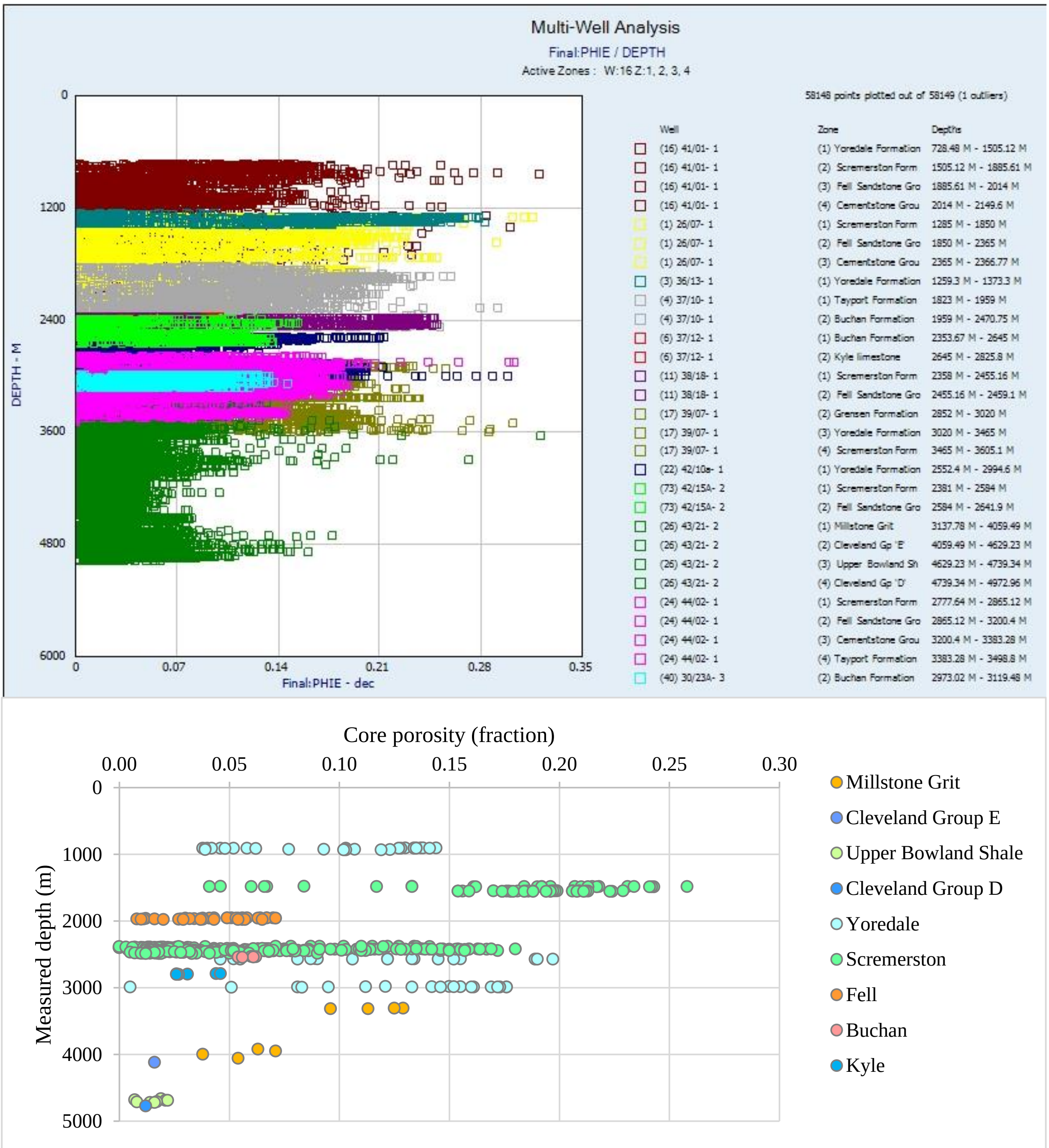


Figure 16 a) Calculated log interpreted porosity (PHIE) versus depth for wells studied in Hannis (2015), each well is a different colour data point. b) Measured core porosity versus depth for the wells examined in the petrophysical study (Hannis, 2015).

Petrophysical work on twelve wells has quantified the most favourable reservoir quality as sandstones in the Yoredale, Scremerston and Fell Sandstone formations (Table 2 below, Hannis, this study).

Formation	NTG (%)	Highest Average PHI (%)	Highest Average PermEst (mD)	Comments
Grensen Formation	0.58	0.12		
Millstone Grit Formation	0.24	0.09	0.15	
Yoredale Formation	0.27	0.19	45.28	Good porosity, although quite low NTG. Slightly better permeability than Fell (in 2 wells)
Cleveland Gp 'E'	0.01	0.07	0.05	
Upper Bowland Shale	0.08	0.07	0.05	
Cleveland Gp 'D'	0.07	0.07	0.07	
Scremerston Formation	0.18	0.15	785.52	Best permeability (in 1 well, poor in 2) Low NTG, but moderate porosity
Fell Sandstone Formation	0.61	0.13	42.69	Best NTG, best porosity, but low permeability (data from 3 wells)
Cementstone Formation	0.11	0.10	0.05	
Tayport Formation	0.49	0.13		Moderate NTG and porosity, no permeability data
Buchan Formation	0.48	0.12		Moderate NTG and porosity, Core data from 1 well, suggests that permeability may be very low
Kyle limestone	0.00	0.11		

Table 2 Synthesis of regional petrophysical screening results by formation on 12 wells suggesting that the Yoredale, Scremerston and Fell Sandstone formations contain sandstones with the most favourable reservoir quality, from Hannis (this study).

Examples of onshore analogues of these reservoir intervals are given in the sections below. Further detailed work is needed at block and prospect level on reservoir extent and quality and the effects of burial history and diagenesis.

3 Review of the Permian petroleum system

3.1 OVERVIEW

This section is a summary of existing work on the working petroleum system within the Permian of the Central North Sea. In Quadrant 30 an example is the Auk Field, and to the south of the current study area an example is the Leman field. Permian rocks of the Central North Sea comprise two sequences – the Rotliegend and the Zechstein Groups. The lower–upper Permian Rotliegend Group primarily comprises sandstones with local basal volcanics and some claystone intervals. Evaporites, carbonates and local clastic rocks make up the upper Permian Zechstein Group (Glennie et al., 2003).

3.2 FIELDS, SHOWS, DISCOVERIES

Permian hydrocarbon fields lie predominantly within Rotliegend strata, typically located in the Southern North Sea (SNS) gas basin. These include the Leman, Indefatigable and Ravenspurn gas fields, which are Westphalian-sourced and range in size (ultimate recovery) from 45 to 328 bcm/1598 to 11583 bcf (Ravenspurn and Leman fields, respectively). Smaller gas fields in this area typically range in size from less than 5 bcm to 20 bcm/177 to 706 bcf (Breunese et al., 2010).

The Carnoustie, Auk, Alma, Ebba and Innes oil fields found around the Auk-Flora ridge are sourced by the Jurassic Kimmeridge Clay formation and contained within Rotliegend reservoirs (Glennie et al., 2003). The P50 ultimate recoverable values for the Auk and Carnoustie fields are 25.8 mcm/157.6 million bbl and 0.1 mcm/0.6 million bbl, respectively (Eriksen et al., 2003).

Gas discoveries (Ralph Cross/Westerdale) have been made in onshore equivalents of the Plattendolomit (Underhill, 2003) as well as offshore in the Plattendolomit (Wissey, Hewett fields).

A systematic search of Permian shows and discoveries across Quadrants 25-44 was out with the scope of this study.

3.3 SOURCE ROCKS

The source rocks to the Rotliegend fields of the Southern North Sea are predominantly underlying Westphalian Coal Measures, as proven by the isotopic studies and their geographical distribution (Gast et al., 2010). Minor source potential exists within the basal oil-prone Zechstein Kupferscheifer, however in this area it is too thin to generate economic volumes of hydrocarbon (only a few metres thick at most, Taylor, 1998).

Oil fields located in the northern part of the Central North Sea (CNS) include the Auk, Alma (originally Argyll), Innes and Carnoustie fields. Hydrocarbons within these fields are sourced from down-faulted Jurassic strata (Glennie et al., 2003).

This study considers Carboniferous and Devonian source rocks underlying the Permian (sections 5 and 6 below).

3.4 RESERVOIR ROCKS

The predominantly aeolian Leman Formation forms the main reservoir for Permian gas fields of the Southern North Sea (Underhill, 2003). The Leman field’s reservoir lies within the Leman sandstone with porosities of 11-14.3% and permeabilities of 0.5-15 mD (Gast et al., 2010). Average porosity and permeability data of Rotliegend gas reservoirs of the Southern North Sea area (Q42 to 49; Figure 17) typically range from 14 to 20% and 0.1 to 2000 mD. The major facies from which these data are taken are dune, wadi and sabkha (Glennie, 1998).

The Auk Formation forms the main Rotliegend reservoir unit in the Northern Permian Basin part of Quadrants 24–44 and comprises mainly reddish brown aeolian sandstones (Glennie et al., 2003). The Auk Formation is a proven reservoir in Quadrant 30 and a potential reservoir in the Forth Approaches basin (see section 5.6 below).

Zechstein carbonates are a proven Permian reservoir in Quadrant 30 with the Hewett, Auk and Ardmore/Alma (originally Argyll) fields. The permeability and porosity of the Zechstein reservoirs of these fields range from 0.02-620 mD up to tens of Darcies (Taylor, 1998). The dolomitic reservoir of the Hewett field has an average porosity of 5-8% and permeability of around 1000 mD (Peryt, 2010).

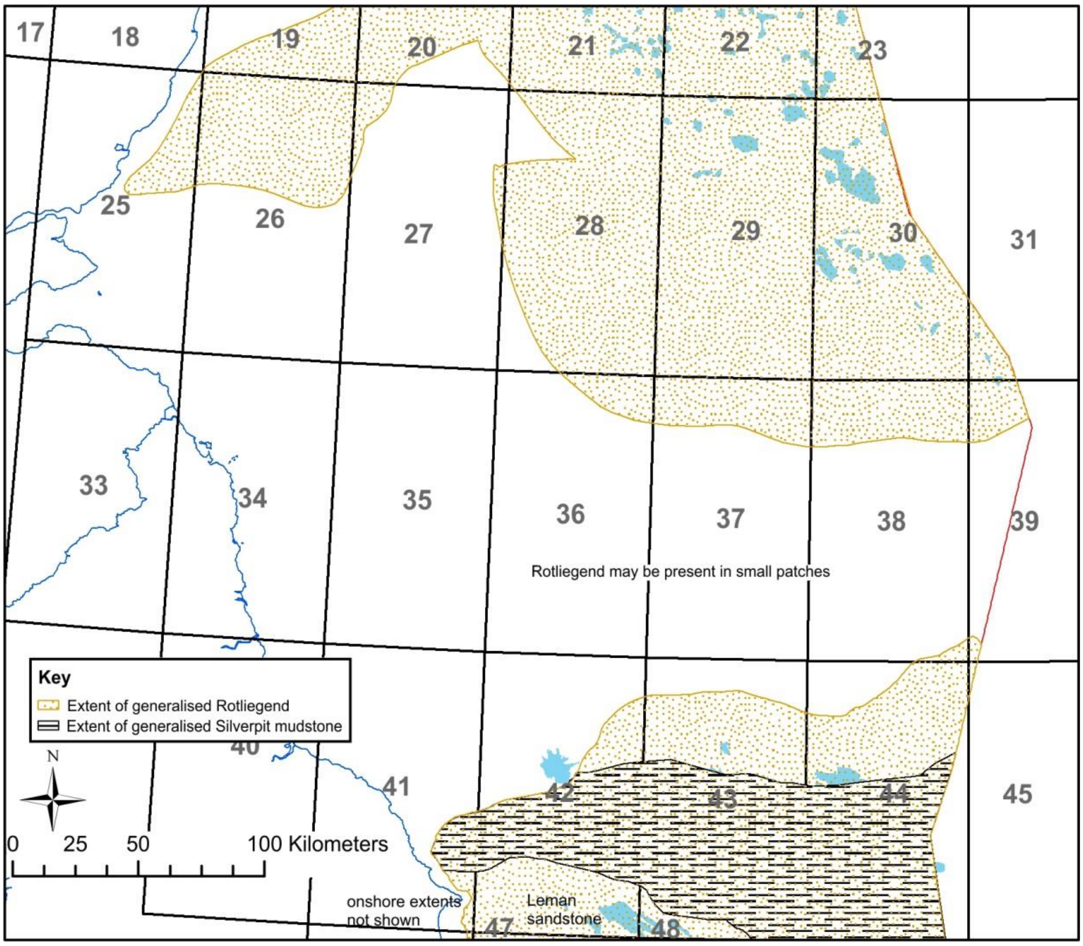


Figure 17 Extent of generalised Rotliegend Group sedimentary rocks, compiled from a number of data sources.

The Permian Mid North Sea High dividing the Southern and Northern Permian Basins is situated in Quadrants 35–39 and the Rotliegend is largely absent across this area (Figure 17). The Cygnus field utilises the Rotliegend reservoir on the northern edge of the Southern Permian Basin (Taggart, 2015) and work is ongoing on mapping small patches of Rotliegend over the Mid North Sea High. The 2015 Government-funded seismic across the Mid North Sea High may help to distinguish patches with preserved Rotliegend sandstones which could provide a migration pathway, a higher porosity reservoir compared with Carboniferous sandstones, or a thief zone for Carboniferous structures.

3.5 SEAL ROCKS

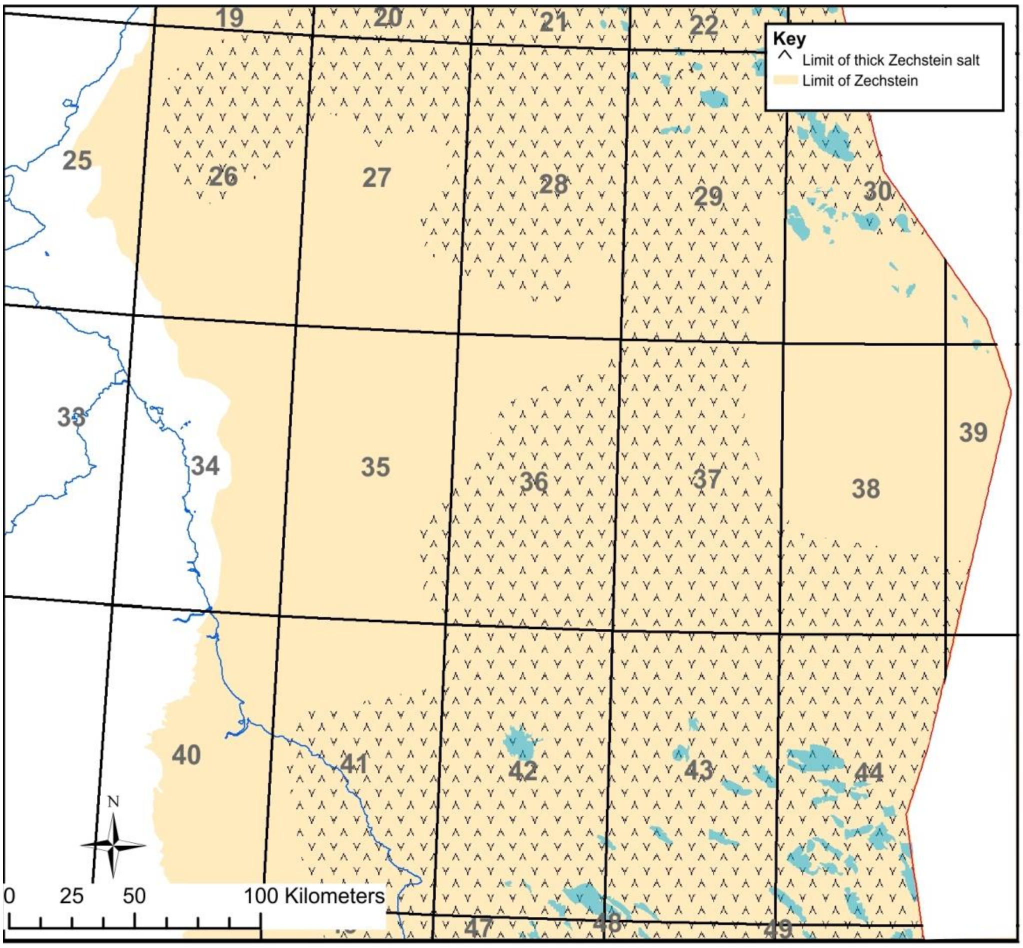


Figure 18 Extent of generalised Zechstein Group, compiled from the Millennium Atlas, Southern Basin Permian Atlas, BGS maps and seismically mapped extents (this study).

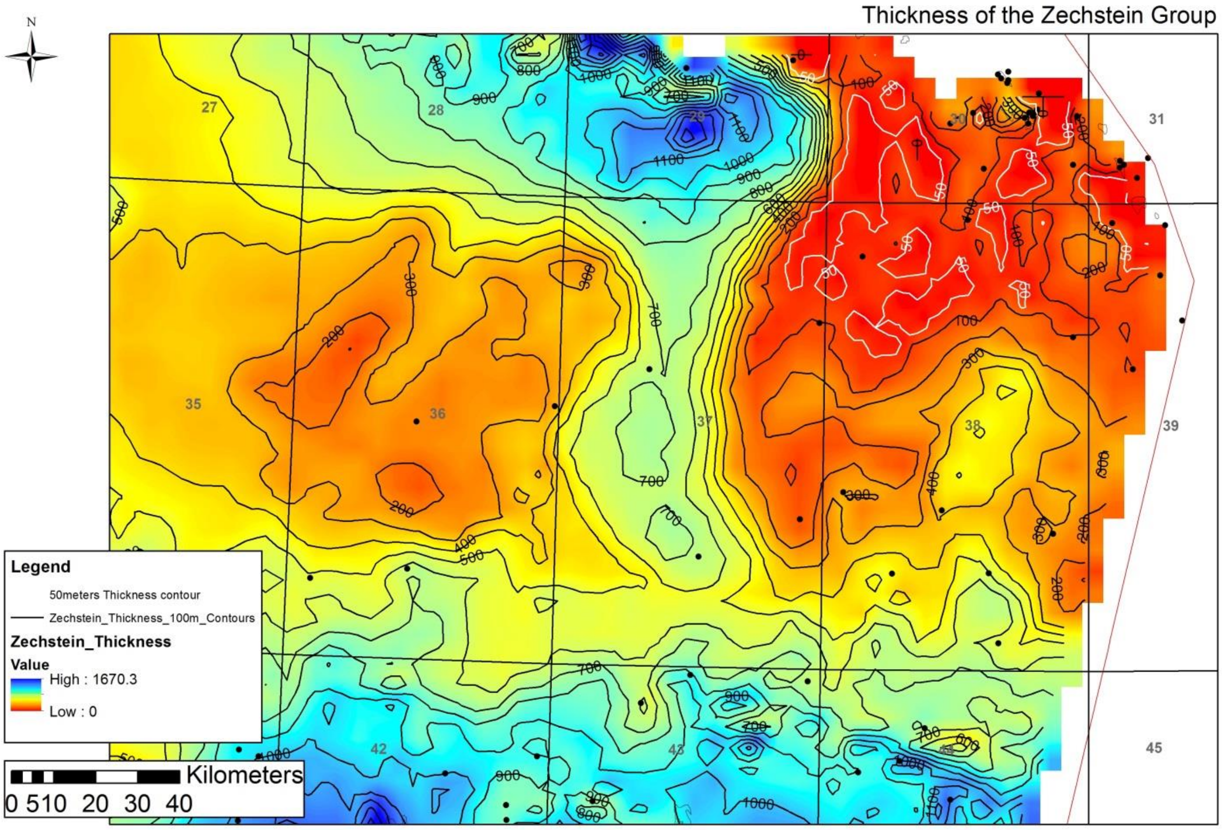


Figure 19 Thickness of the Zechstein Group (in metres) calculated from depth converted 5 km grids from Arsenikos et al. (this study). Note the white contour is 50 m.

The regional top seal to Rotliegend and Carboniferous reservoirs is provided by Zechstein evaporites (Figure 19). Thicknesses of the evaporite facies can vary from less than 50 m to over 1500 m (Cameron et al., 1992a) and as mapped in this study (Figure 19). Carbonate and anhydrite facies are also present, particularly within the lower Zechstein, which in part act as seals, but can also act as reservoirs (Glennie et al., 2003).

The desert playa Silverpit formation comprises shales and evaporites that act as a local seal. Thicknesses can reach over 300 m (Cameron et al., 1992b). The system is a lateral equivalent to the Leman sandstone (Figure 20).

3.6 TRAPS

In the SNS, most Rotliegend traps have broad north-west–south-east-trending fault-dip closures. The closures were formed by Alpine orogenic transpression during Late Cretaceous and Tertiary inversion (Glennie & Provan, 1990). Structures on similar trends are mapped in Quadrants 43 and 44 from the Silverpit Basin towards the Farne Granite (Figure 6).

3.7 MATURITY, MIGRATION AND CHARGE

Charge to the southern gas fields is predominantly from mature Westphalian strata (see section 4.7), while to the northern oil fields charge is from downthrown Jurassic strata, requiring vertical migration through fault conduits (Glennie et al., 2003). Organic matter from the Kupferschiefer formation has 0.6-0.9% VR, indicating the formation is mid-mature for oil (Peryt et al., 2010).

3.8 RISKS

The components of the working petroleum system are present across Quadrants 25-44 however difficulties in seismic imaging beneath the Zechstein evaporites and variability in reservoir and seal presence, facies and thickness reduce prospectivity in some parts of the study area. Key risks include:

- Thinning out of Zechstein seal in areas such as 42/18 and along the north-eastern margin of the North Dogger Basin
- Variability of the quality of the Silverpit seal, where sandy intervals occur and replace the finer grained sediment
- The northern edge of the Rotliegend sandstone can be absent or salt-plugged, the sandstone quality is variable and potential reservoirs pinch out, leading to diminished reservoir quality
- Prediction of the reservoir quality within the Zechstein carbonates is difficult due to rapid lateral variability
- Extent of restricted areas of Rotliegend sandstones across the Mid North Sea High

4 Review of the Westphalian petroleum system – Southern North Sea gas fields

4.1 OVERVIEW

This section is summary of existing work on the producing petroleum province present in the south of the study area (southern Quadrants 43, 44 including the Cygnus, Cavendish, Kilmar, Trent, Boulton, Schooner, Ketch, Tyne, Wingate fields; see Figure 3 for generalised extent). The Westphalian sequence is absent over much of Quadrants 25–42 (Figure 5). Knowledge of proven Westphalian gas fields was used to inform the Namurian and older Carboniferous plays studied here.

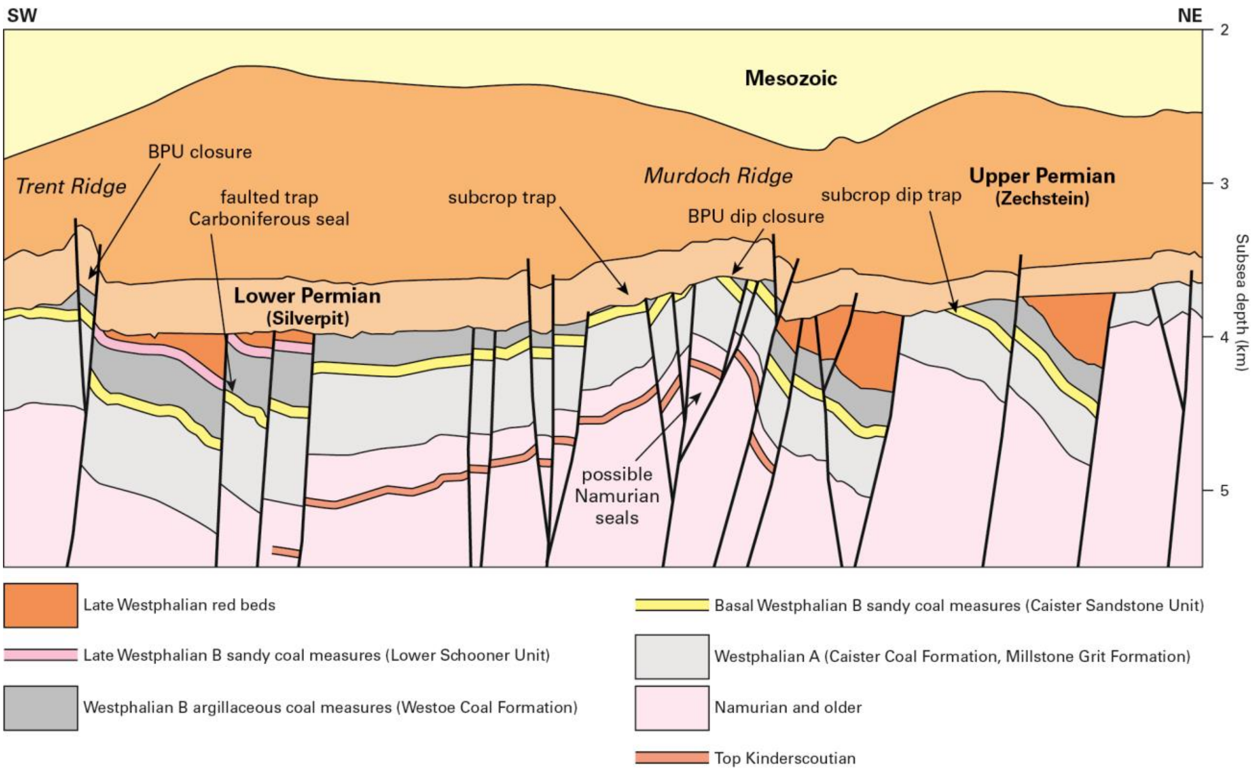


Figure 20 Summary of Westphalian petroleum systems redrawn from Cameron et al. (2005). Reproduced with permission of the Yorkshire Geological Society.

4.2 FIELDS, SHOWS, DISCOVERIES

The Southern North Sea Westphalian gas fields are a major, producing petroleum system located in the southern parts of Quadrants 43 and 44 and north-eastern Quadrant 49. Late Westphalian (Bolsovian to Asturian, Ketch Formation/Schooner unit) fields include Ketch, Schooner, Boulton and Tyne in Quadrant 44, with gas accumulations in the adjacent Dutch blocks D, E and K (Cameron et al., 2005; Kombrink et al., 2010). Sandstones within the Caister Formation form the reservoir within the Caister, Murdoch, Trent and Cavendish fields and a latest Namurian reservoir occurs in Cavendish (Cameron et al., 2005; Kombrink et al., 2010).

Westphalian-sourced, Rotliegend-reservoired fields are generally located in the far south of Quadrant 42 and Quadrants 47-49, the exception being the Cygnus field (44/11 and 44/12) with Ketch and Rotliegend reservoirs on the northern edge of the Silverpit basin.

Typically Westphalian gas fields range from 3.28 bcm/116 bcf (Trent) to 81 bcm/2860 bcf (Indefatigable and Indefatigable Southwest, Breunese et al., 2010).

4.3 SOURCE ROCKS

Westphalian coals are the main source rocks for Westphalian and Rotliegend gas fields in the Southern North Sea (Kombrink et al., 2010). Some contribution from Namurian shales may be possible e.g. in the Trent field (Kombrink et al., 2010). Marine shales within the coal bearing cycles contain Type II oil prone kerogens (Pletsch et al., 2010).

4.4 RESERVOIR ROCKS

The Ketch Formation pebbly sandstones form the most important Carboniferous reservoirs in the Southern North Sea (Kombrink et al., 2010). Reservoir sand bodies are also present in Westphalian A and B Coal Measures strata. In the Trent field (block 43/24), the reservoir interval is late Namurian-early Langsettian in age including Millstone Grit delta-top facies (Cameron et al., 2005; Kombrink et al., 2010).

Within the Westphalian Coal Measures, porosities are between 3 and 19% with permeabilities of 0.1 to 11 mD. The Westphalian red beds (e.g. Ketch Formation) fare better, with average porosities ranging from 7 to 20% and permeabilities of 10 to 1000 mD (Besly, 1998).

4.5 SEAL ROCKS

The shales and evaporites of the Silverpit Formation (Rotliegend equivalent) in the Silverpit-Cleaver Bank area, and Zechstein evaporites form the regional seal (Figure 22). Some intraformational sealing by mudstones has been documented e.g. Duckmantian mudstones in the Boulton field, (Kombrink et al., 2010)

4.6 TRAPS

Late Carboniferous-early Permian Variscan inversion, uplift and folding along with NW-SE/WNW-ESE and NE-SW faults formed many structural traps of the Westphalian SNS play (Cameron et al., 2005; Fraser and Gawthorpe 1990; Figure 20). Dip and fault closures adjacent to the Base Permian unconformity (Variscan) and Permian seal rocks form a major trap type (Pletsch et al., 2010). Seismic mapping for this study indicates that north-west trending faults and associated folding continues from the Westphalian play to the Namurian sequences in northern parts of Quadrants 43 and 44.

4.7 MATURITY, MIGRATION AND CHARGE

Though there is local variability, large parts of the Coal Measures in the Southern North Sea are within gas window. Generation was widespread until Mid-Jurassic times with renewed generation and migration during the Neogene (Pletsch, 2010). Migration is believed to be local from coal to sandstones. Northwards migration of Westphalian (Coal Measures) -sourced gas has previously been hypothesized to older reservoirs in Quadrant 42 (e.g. RWE Dea, 2011b)

4.8 RISKS

Within the working petroleum system, risks include quality of seismic imaging, complex subcrop beneath Permian seal, correlation of stratigraphy in red-bed strata and variations in reservoir quality (Henderson, 2013).

Further research on the intraformational Carboniferous sealing observed in some Westphalian fields (e.g. Boulton, Conway & Valvatne, 2003) could be of particular relevance to similarly faulted and folded lower–mid Carboniferous structures to the north of the Westphalian subcrop.

5 Results: Lower–mid Carboniferous petroleum systems

The lower–mid Carboniferous (Visean-Namurian) age clastic petroleum systems are the main focus of this study across Quadrants 25–44. A clastic fluvio-deltaic system with periodic marine incursion dominates across the northern-central part of the area – the ‘lower–mid Carboniferous clastic play’. In the southern part of the area, coeval deeper water, basinal facies were deposited giving a distinctly different ‘lower–mid Carboniferous basinal play’ (Figures 4, 23). Palaeogeographic reconstructions highlight the longevity of this distinction from the Arundian to Pendleian (Kearsey et al., this study, and Figure 21).

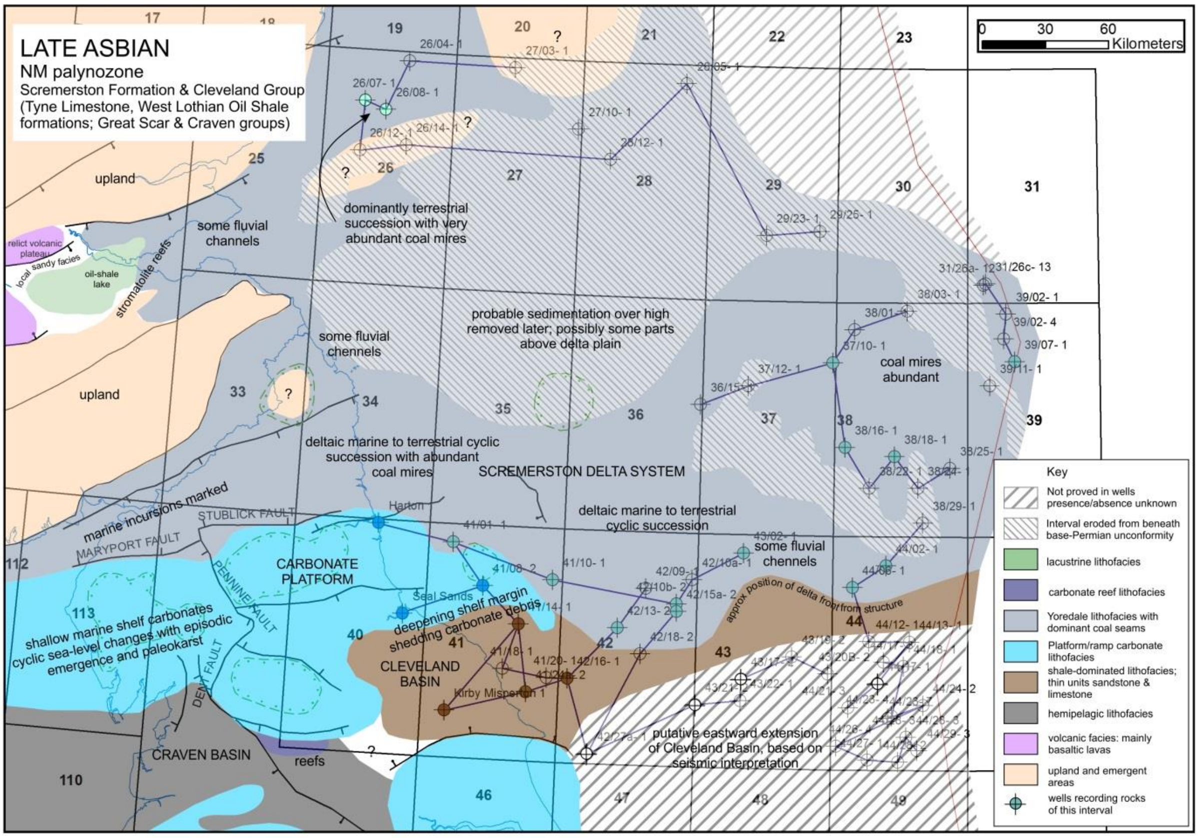


Figure 21 Example of late Asbian (early Carboniferous) palaeogeographic map (gross depositional environments) with clastic deltaic systems ‘clastic play’ (in grey) passing southwards to a shale-dominated basin ‘basinal play’ (in brown; from Kearsey et al., this study). Wells in which the unit is proven are coloured.

Similar to the Westphalian Coal Measures, Visean-Namurian strata (Fell, Scremerston, Yoredale, Millstone Grit formations and basinal Cleveland Group units) are commonly heterolithic and cyclical (Figure 22), responding to variations in sea level, tectonics and sediment supply. Source rocks – mudstones, carbonaceous mudstones, coals, oil shales and bituminous limestones – occur in close proximity to reservoir rocks - mainly coarse channel sandstones or transgressive beach sandstones. Intraformational seals could be provided by extensive mudstones. The data available is not suggestive of a reservoir facies within the limestones.

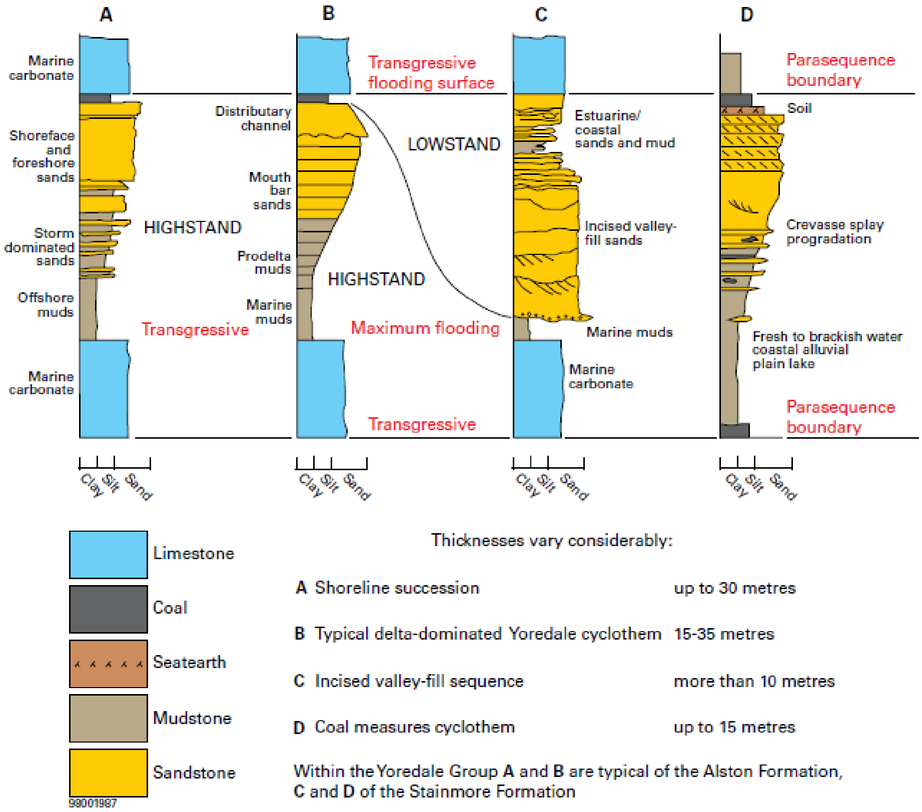


Figure 22 Examples of heterolithic clastic sequences with in the Yoredale Group onshore, from the BGS Regional Guide to Northern England after Tucker et al. (2003). Similar packages are observed in well logs and cores offshore.

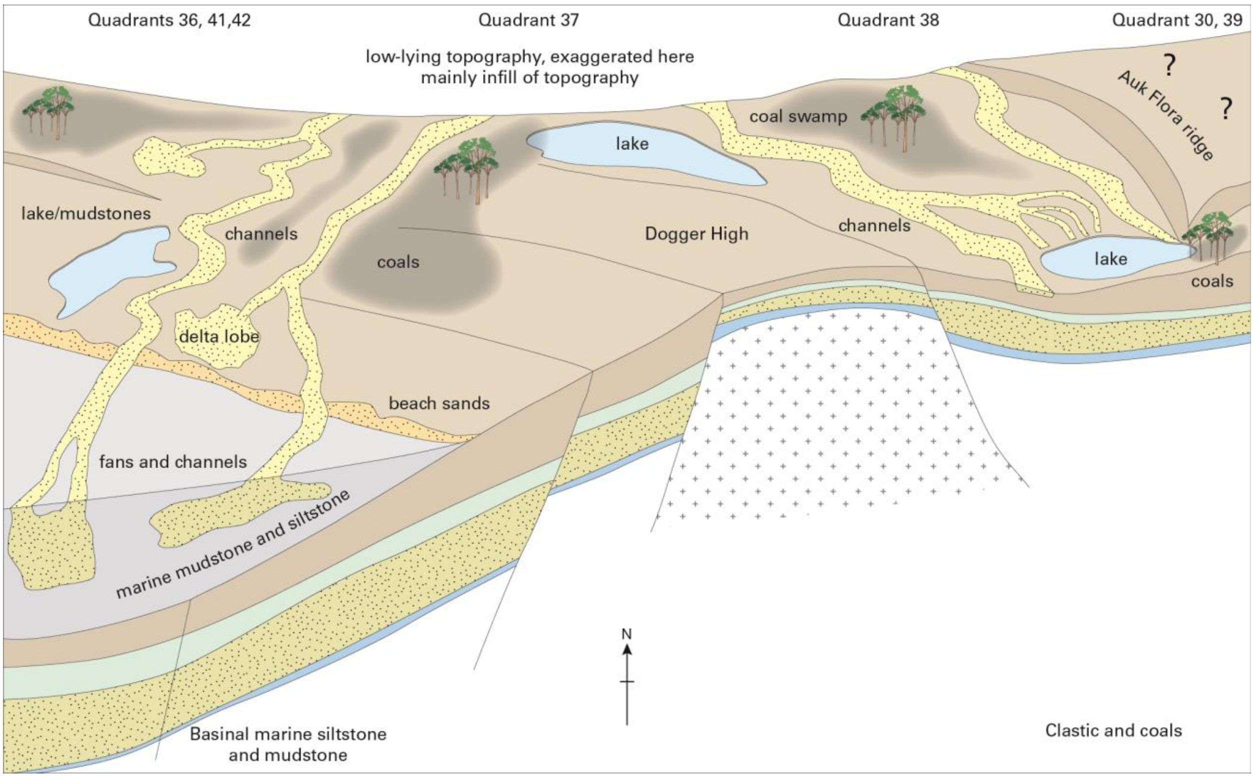


Figure 23 3D generalised cartoon of structure and lowstand depositional environments in Scremerston/Yoredale formations across the southern part of the study area (Quadrants 35–44). The topography on the cartoon is exaggerated for effect – sedimentation is interpreted to have kept pace tectonism such that fault scarps would not have been exposed. The 'clastic play' on the top and right of the figure contrasts with the 'basinal play' on the bottom left. During highstands, marine incursions occurred across the fluvio-deltaic plain.

5.1 EXTENT MAPS AND SELECTED DEPTH AND ISOPACH MAPS

Regional maps derived from well and seismic interpretation (see Kearsey et al, this study, Arsenikos et al, this study and Figure 7 for data distribution) are presented together in this section. These are followed by an account of each sub-area and its petroleum system, which refers back to the these regional maps.

The Pre-Permian subcrop map (Figure 5) and extent maps (Figures 24-27) indicate the widespread interpreted extent of the intercalated potential source and reservoir-bearing units across the area. The extent maps are annotated to give an indication of average maturity for each stratigraphic unit.

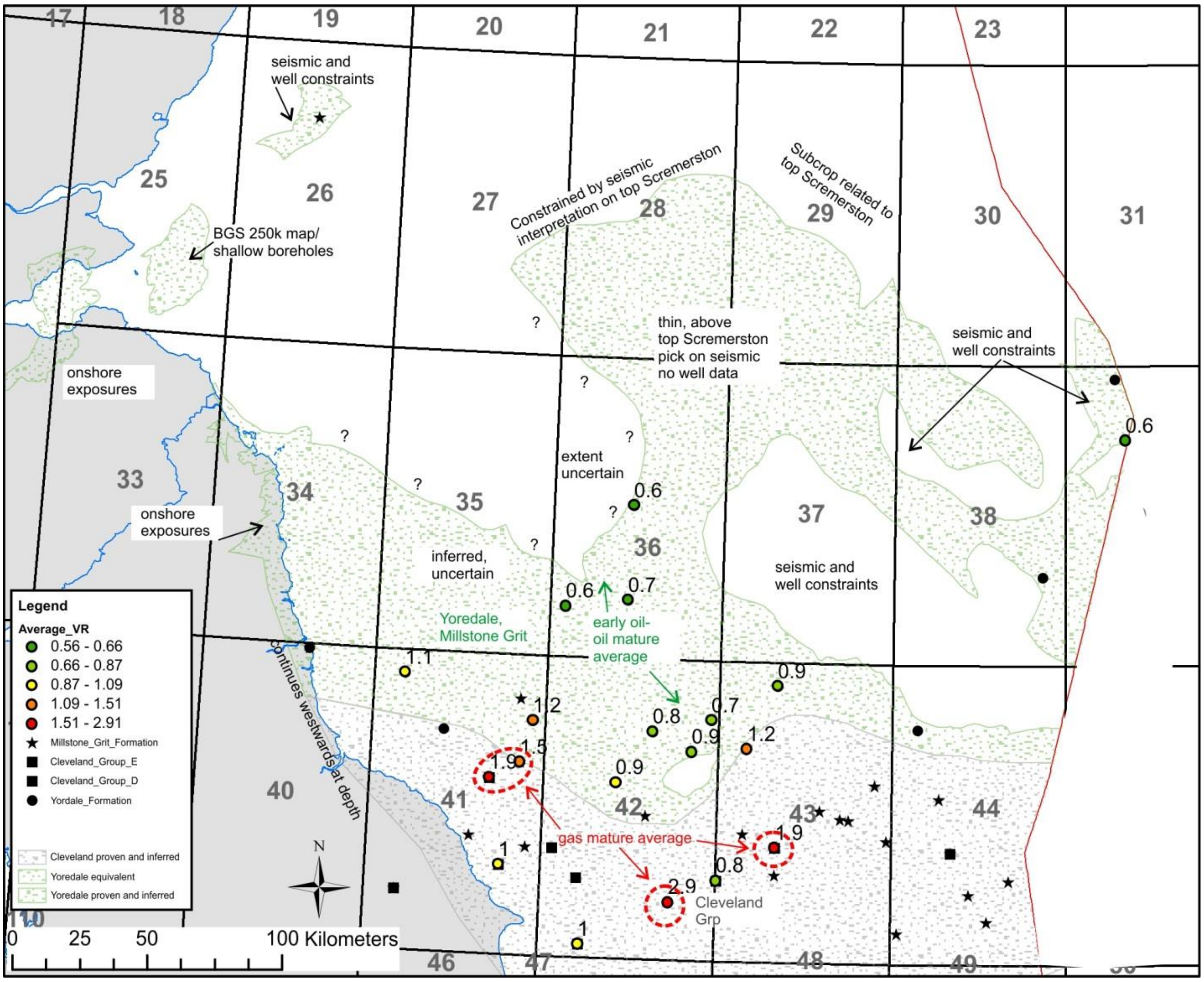


Figure 24 Interpreted extent of Visean-Namurian Yoredale, Millstone Grit and laterally equivalent basinal Cleveland Group D/E, Upper Bowland Shale units, together with average maturity values for the Yoredale/Cleveland D/E from measured and calculated vitrinite reflectance data in wells.

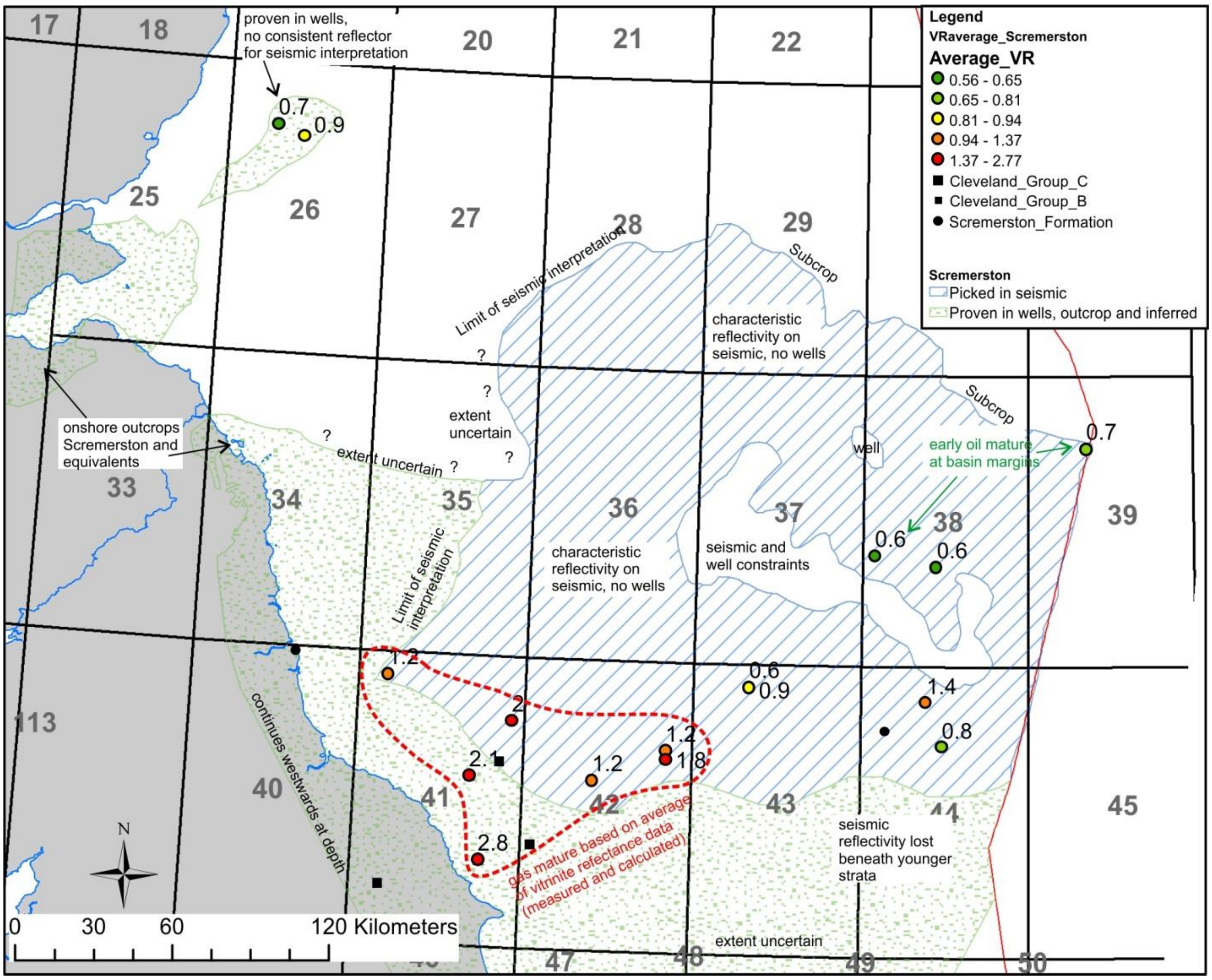


Figure 25 Extent of late Asbian Scremerston, Firth Coal formations and laterally equivalent basinal Cleveland Group B/C units, together with measured and calculated average maturity values from vitrinite reflectance data in wells.

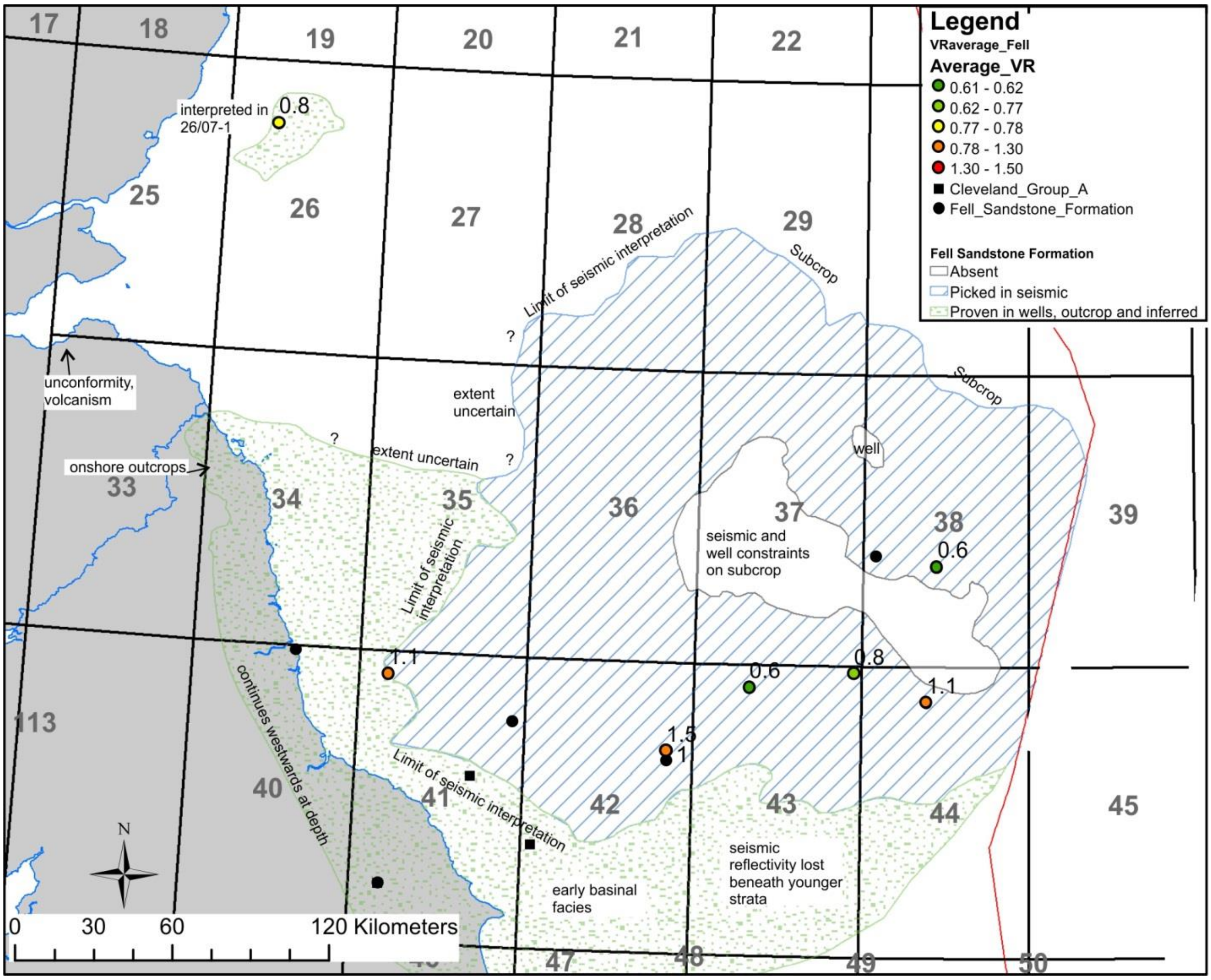


Figure 26 Extent of Arundian Fell Sandstone Formation and laterally equivalent basinal Cleveland Group A unit, together with measured and calculated average maturity values from vitrinite reflectance data in wells. Note that in Quadrant 26, the unit of this age has previously been named the 'Tayport Formation' – in this study the Chadian–Holkerian age unit is correlated with the Fell Sandstone Formation.

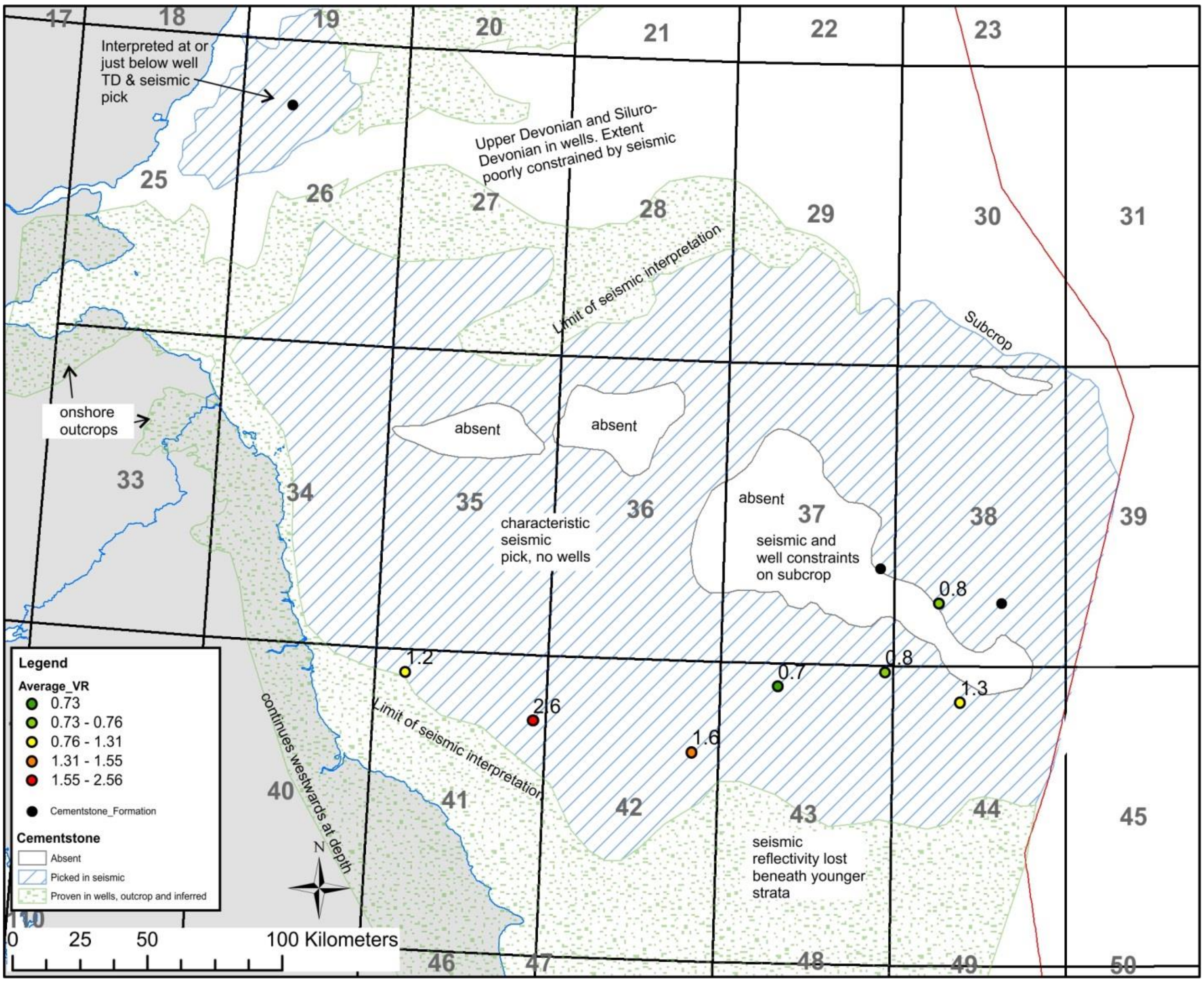


Figure 27 Extent of Tournaisian Cementstone Formation together with average maturity values from vitrinite reflectance data in wells.

As indicated by the subcrop map (Figure 5), lowermost Carboniferous and upper Devonian sandstones are believed to be present across much of the study area and absent only on the regional highs such as the Devil's Hole Horst. The extent of the Mid Devonian Kyle Group is shown in section 6 below.

Depth maps for the top Scremerston Formation and top Kyle Group and selected isopachs are shown (Figures 28–31). Further maps are given in Arsenikos et al. (this study) and 5 km resolution grids are available digitally. These maps are intended to give the regional context of blocks and basins for more block/prospect specific work, and have been incorporated into the basin modelling study (Vincent, this study). For example, the regional high of the top Kyle Group as tested by the 37/25- 1 well dominates the depth grid on Figure 29 and the Breagh field high can be seen at Top Scremerston level on Figure 28.

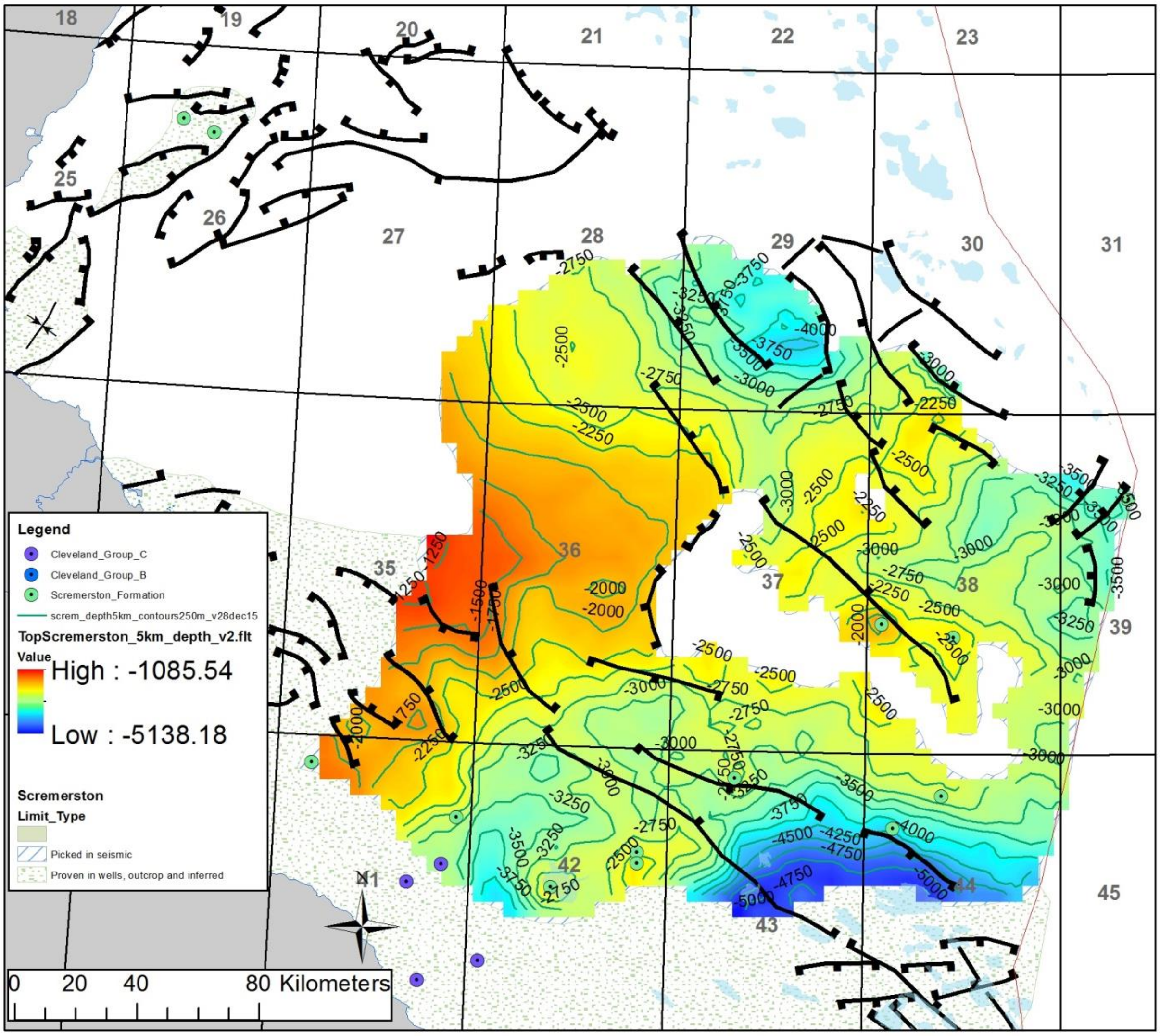


Figure 28 5 km resolution seismic depth grid (in metres) to Top Scremerston Formation and lateral equivalents, shown with the major regional scale faults.

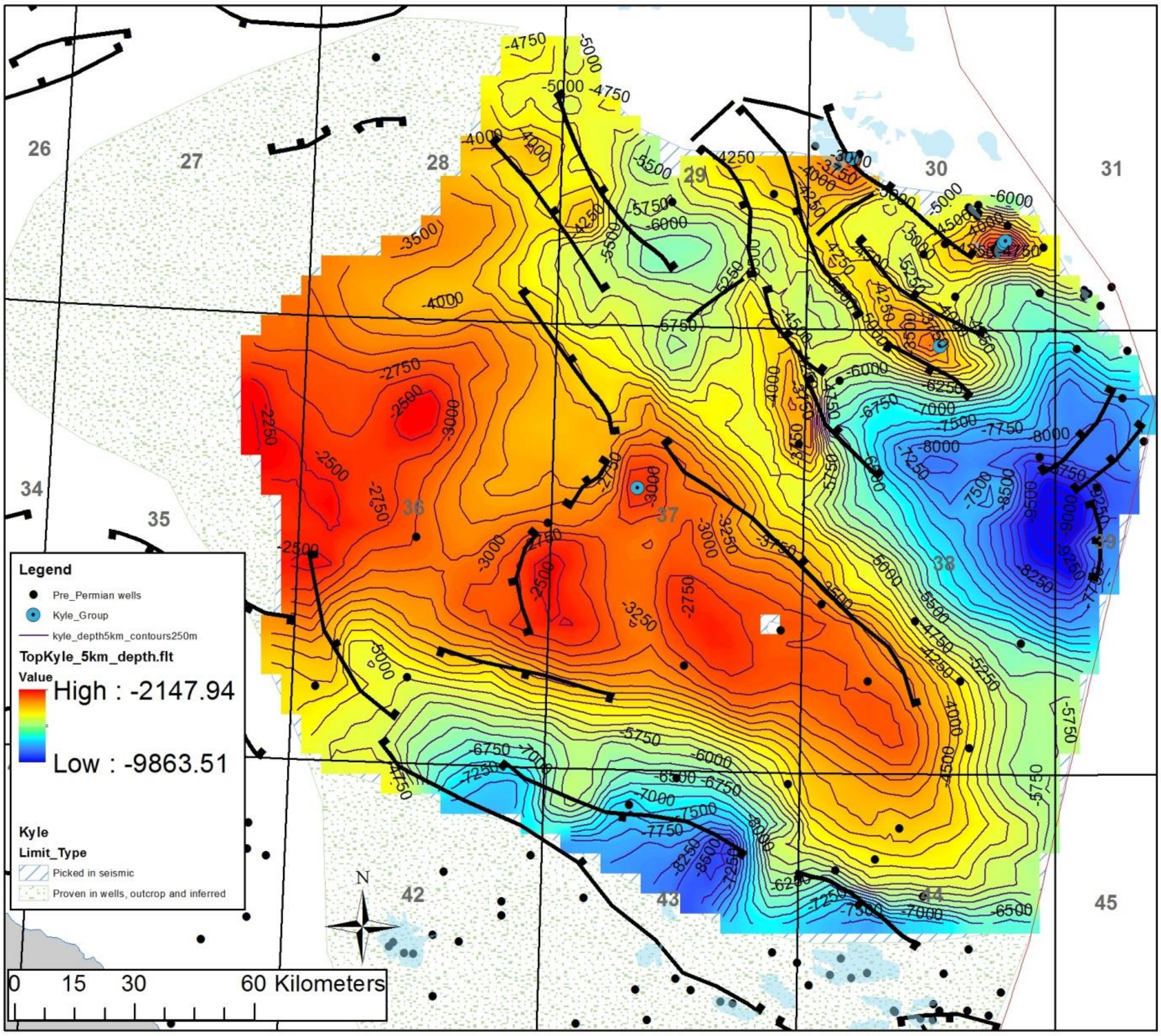


Figure 29 5 km resolution seismic depth grid (in metres) to Top Kyle Group and lateral equivalents, shown with the major regional scale faults.

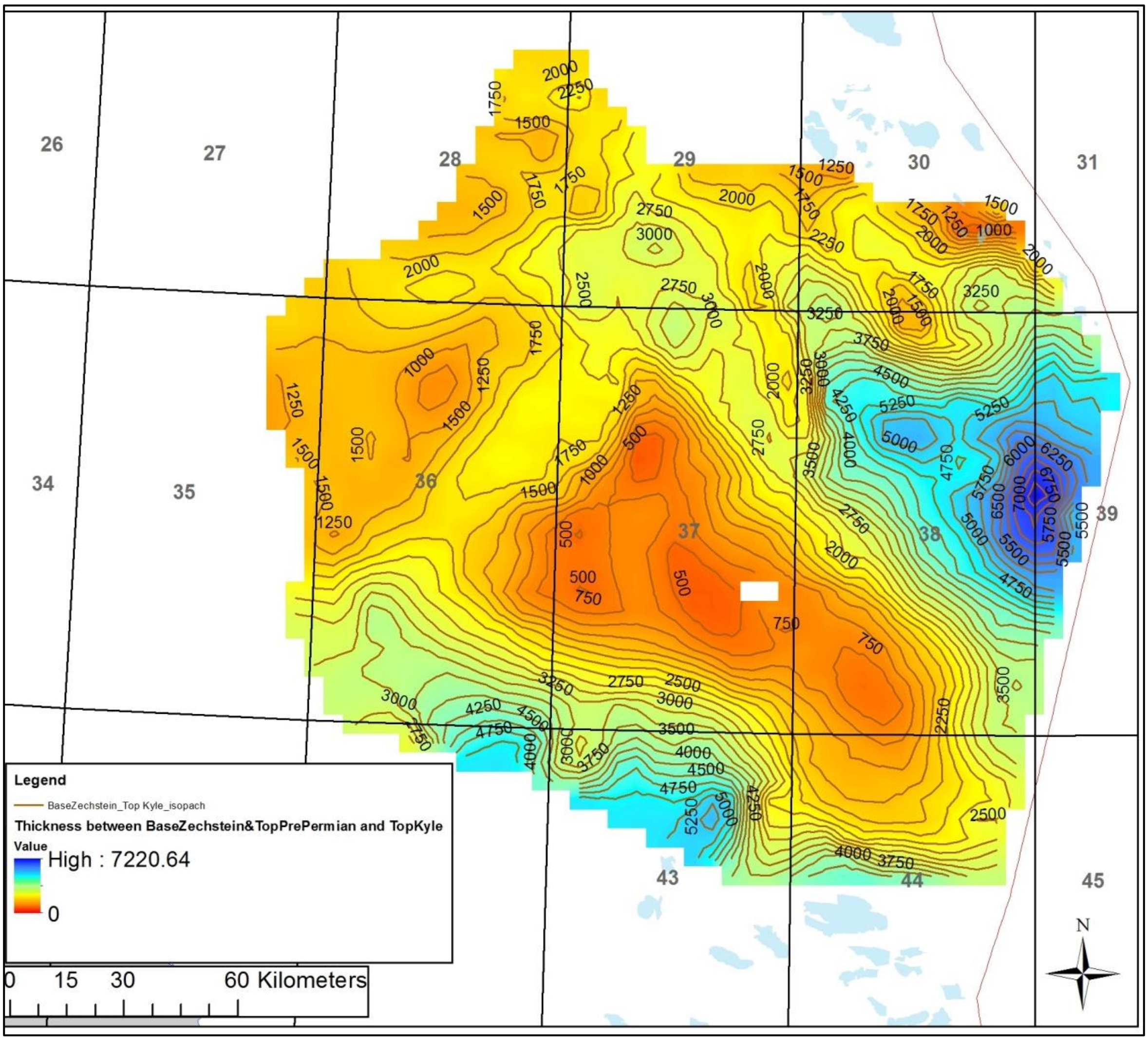


Figure 30 5 km resolution isopach (in metres) from Base Zechstein/top Pre-Permian to top Kyle Group to give an indication of the Carboniferous and upper Devonian thickness.

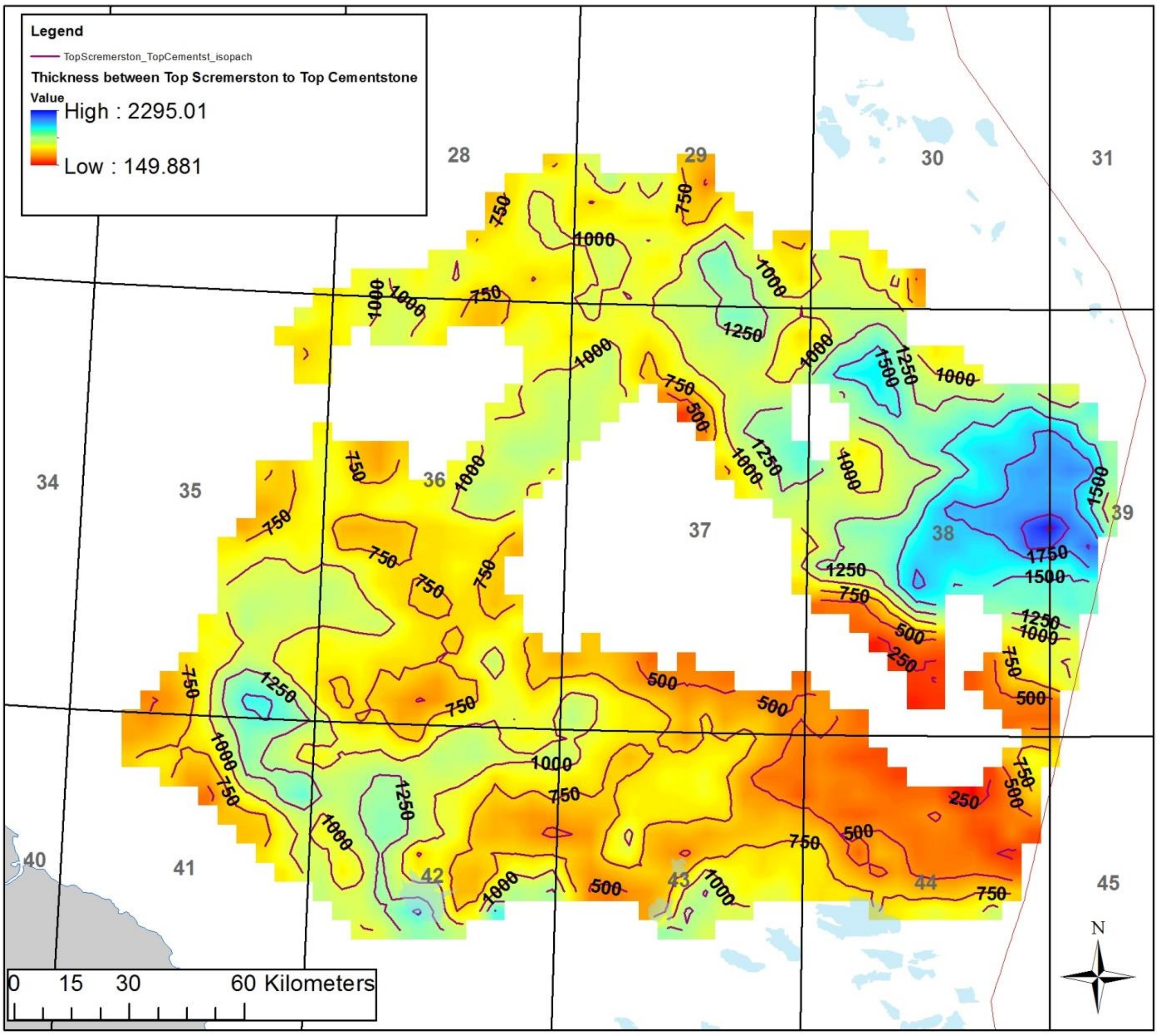


Figure 31 5 km resolution isopach (in metres) from Top Scremerston Formation to top Cementstone Formation to give an indication of Visean (Scremerston, Fell Sandstone and lateral equivalents) thickness.

5.2 LOWER–MID CARBONIFEROUS CLASTIC AND BASINAL PLAYS ON THE SOUTHERN MARGIN OF THE MID NORTH SEA HIGH

5.2.1 Overview

The Breagh Field (block 42/13) proves a working lower Carboniferous clastic play on the southern margin of the Mid North Sea High (MNSH). A relatively thin but spatially extensive lower–mid Carboniferous succession subcrops the base Permian unconformity to some distance north of Breagh. Southwards of Breagh/southern Quadrants 41–44, substantial thickening is observed into the Cleveland and Silverpit Basins (Figures 30, 32, 33). Well correlations show that the thick, mudstone- and siltstone-dominated basinal play interfingers with, and passes laterally to, the fluvio-deltaic clastic play throughout the early–mid Carboniferous (Figure 32 and Figure 23 above), with a transistional zone noted in the Cleveland Group C unit in Quadrant 41 (Kearsey et al. this study).

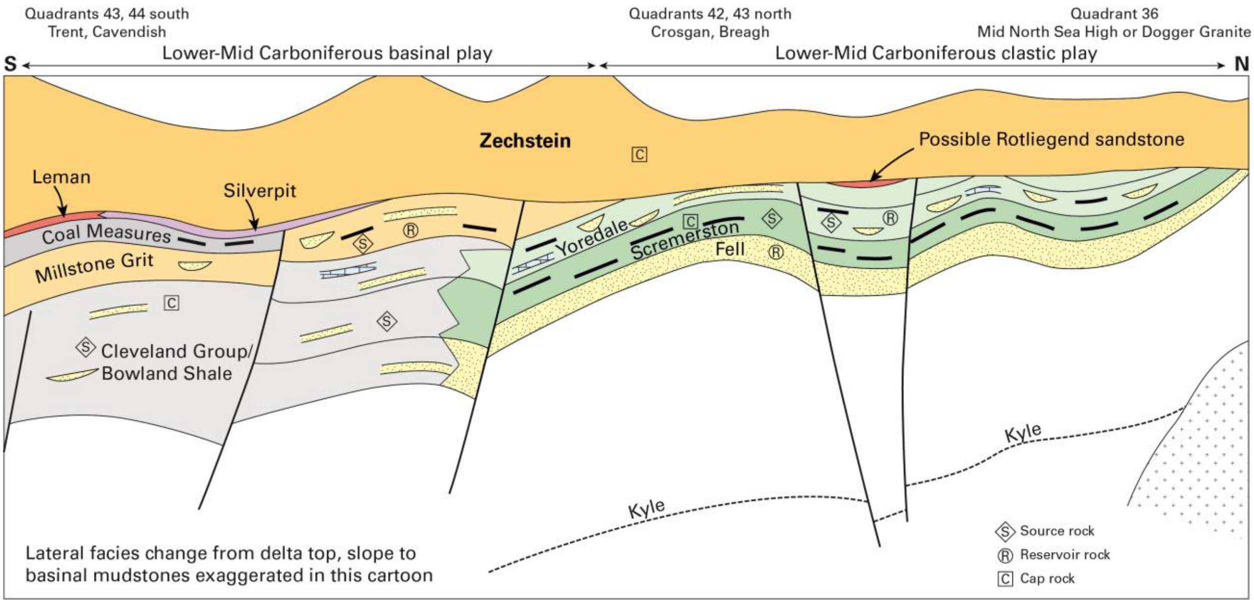


Figure 32 Cartoon of the lower–mid Carboniferous clastic to basinal play system. The facies change is greatly exaggerated – in reality it is gradational and interfingering, and in some areas occurs on a regional slope as opposed to across a fault.

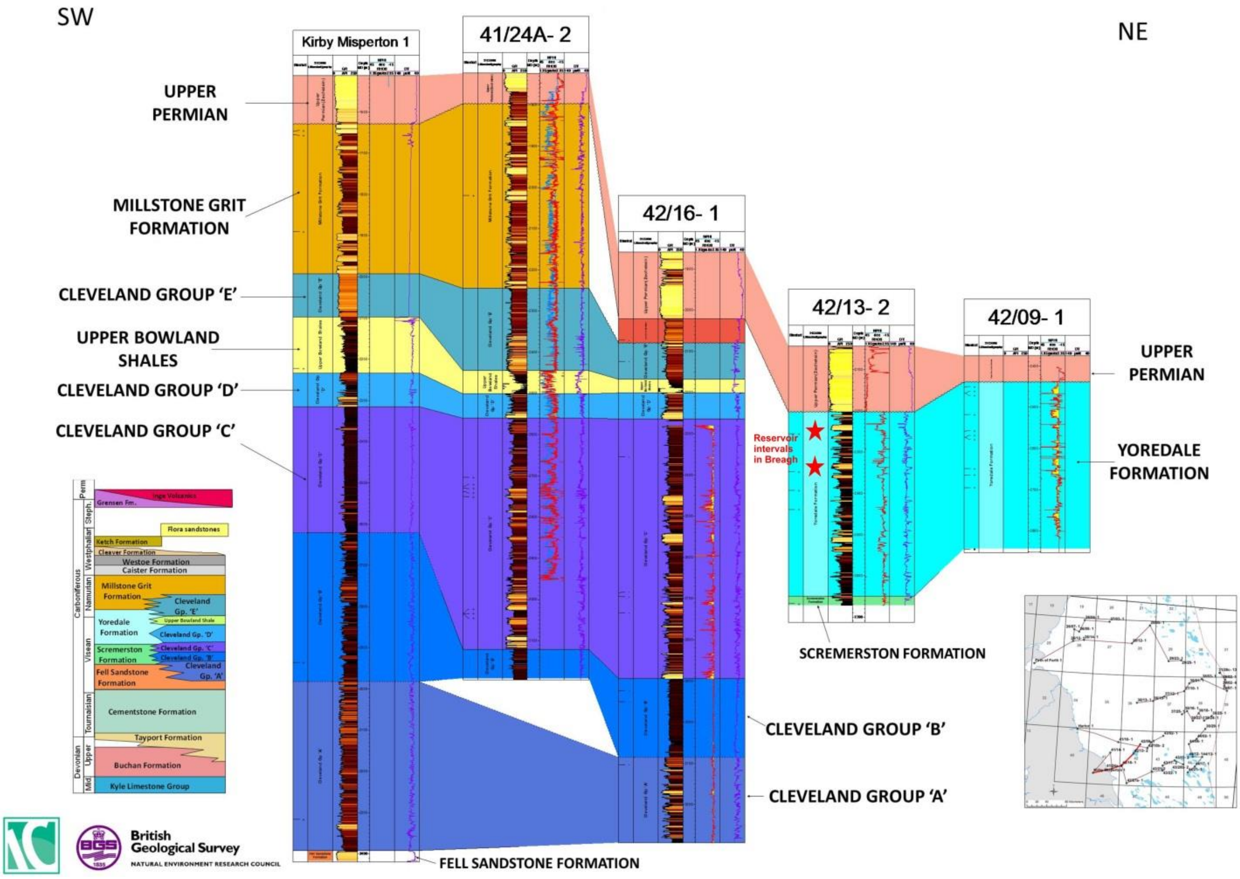


Figure 33 North-east to south-west correlation line from Yoredale type facies of the clastic play to Cleveland Group facies of the basinal play

In the north of Quadrants 41–44, the top Scremerston Formation is at depths of around 3km with some regional highs and basins observable in the 5 km resolution regional grid (Figure 28). To the north-east, the Carboniferous units onlap the Dogger Granite regional high. A north-south basin west of Breagh contains a relatively thicker Top Scremerston-Top Cementstone interval of up to 1.25 km (Figure 31). In Quadrants 43–44 the top Scremerston Formation plunges deeply to 5 km depth beneath the younger Carboniferous strata of the Silverpit basin. The lower–mid Carboniferous succession in the south of Quadrants 41–44 is proven in wells to be over 2 km thick. The geometry is an important control on source rock maturity and on trapping.

Recent studies by Rodriguez et al. (2014) and Parsons (2015) have considered potential of the lower Carboniferous play on the southern margin of the Mid North Sea High.

5.2.2 Fields, shows, discoveries

The Breagh Field (block 42/13) commenced production in 2013 and is believed to host 19.8 bcm/699 bcf gas (DEA Group, 2015). The reservoir intervals comprise a number of channel sandstones within the Yoredale Formation (Brigantian age). The field is situated on a regional high and is trapped beneath the Zechstein seal.

The nearby Crosgan discovery (42/10b-2, 42/15b- 2) contains gas, estimated at 185 bcf GIP/5.2 bcm within the Yoredale and Scremerston formations (P50, Premier Oil, 2008). The structure is a faulted dome at subcrop with the Permian unconformity.

A number of other shows are present within the lower Carboniferous, generally on the northern side of Quadrants 41–44 (Figure 34).

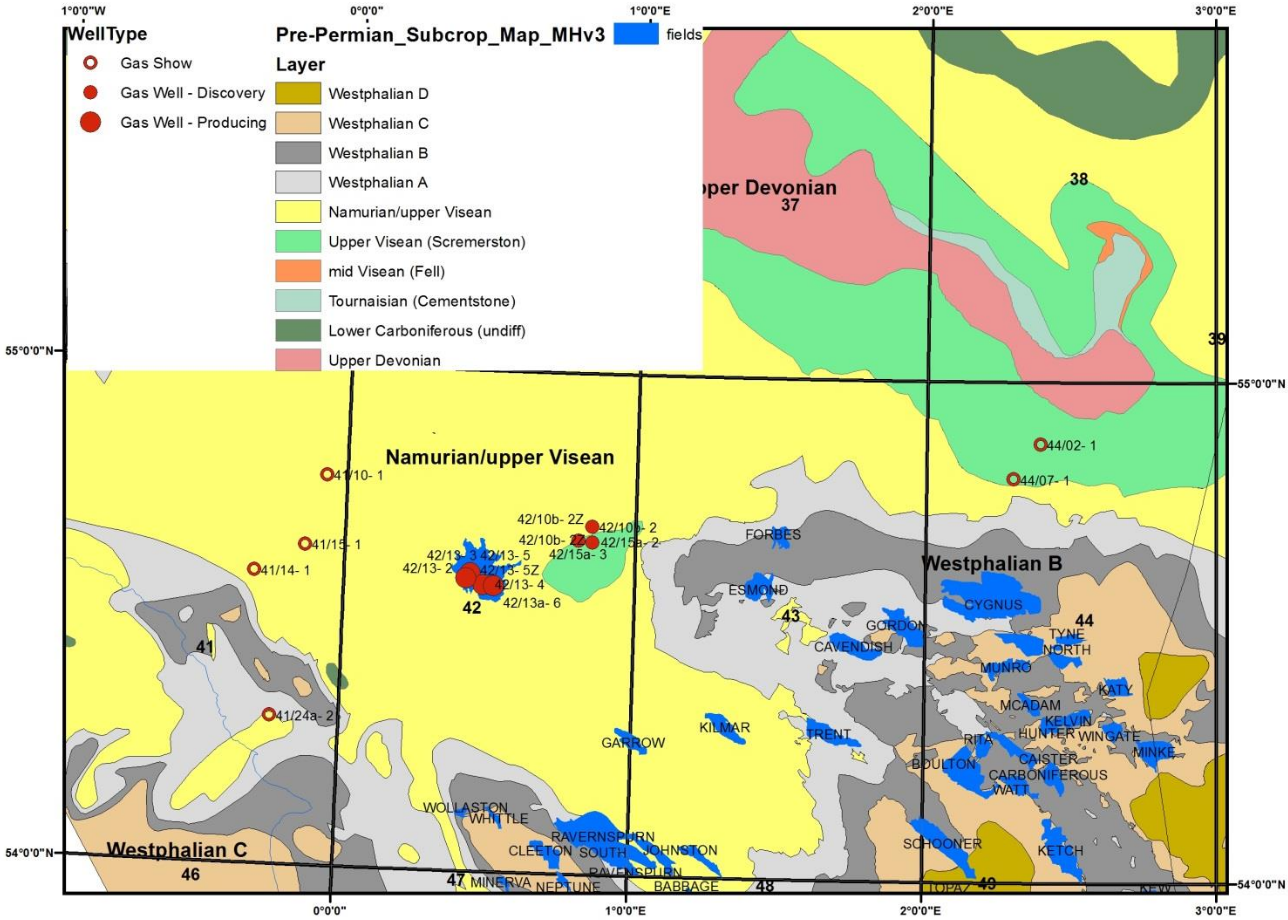


Figure 34 Shows, discovery and producing wells in lower Carboniferous (Visean) reservoirs from a literature review superimposed upon the pre-Permian subcrop map. Shows/discoveries are located in the Scremerston Formation and lower parts of the Yoredale Formation (beneath the Great Limestone equivalent).

Shows and discoveries in Namurian reservoirs (upper parts of the Yoredale and Millstone Grit formations) are more widespread across Quadrants 41–44 including in the Trent field (Figure 36).

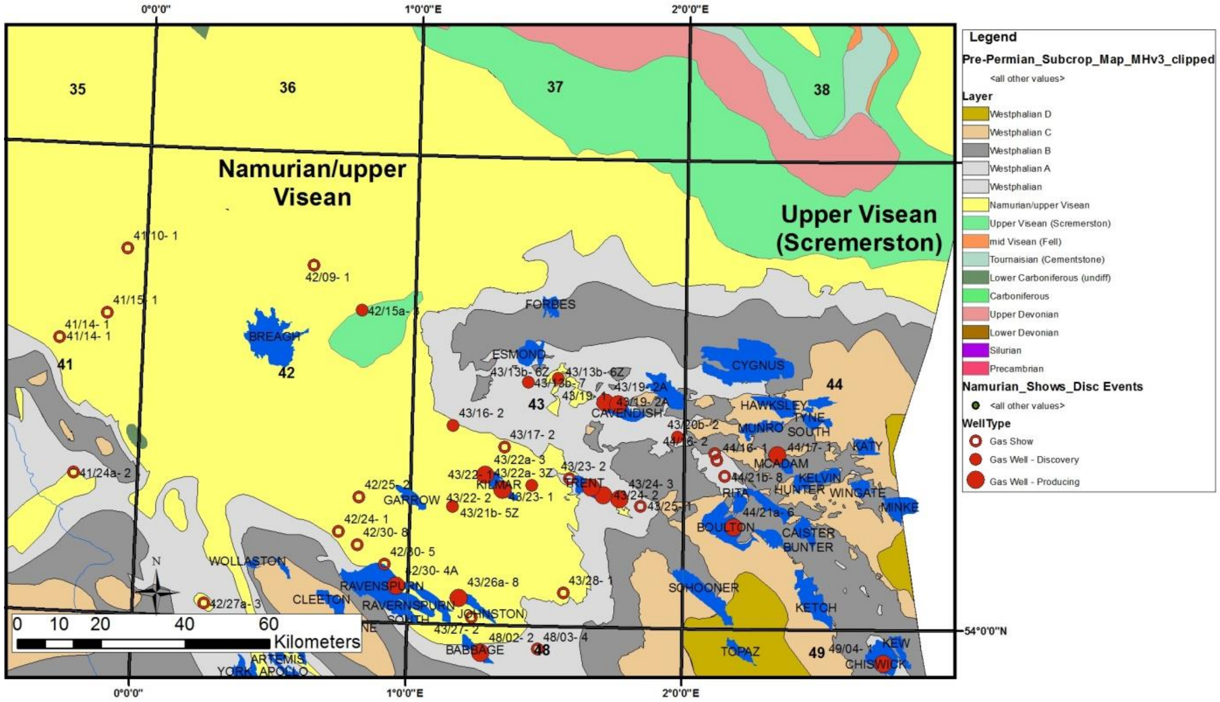


Figure 35 Shows, discovery and producing wells in Namurian reservoirs (upper parts of the Yoredale Formation and the Millstone Grit Formation plus upper parts of the Cleveland Group) from a literature review.

Geochemical studies of hydrocarbons in fields, shows and fluid inclusions indicate a dominant non-marine Carboniferous source across much of Quadrants 42 and 43 with one instance of a Carboniferous marine source in the southern part of Quadrant 41, coincident with the basinal play (Figure 11 above, see Vane et al., this study for literature review).

Onshore of Quadrant 41, the Caythorpe, Eskdale, Kirby Misperton, Lockton, Malton, Marishes and Pickering gas fields are believed to be sourced from highly mature Namurian coals and shales and are produced from faulted traps (Pletsch et al., 2010, Figure 1).

5.2.3 Source rocks

Numerous source rock intervals are found within lower–mid Carboniferous strata on the southern side of the MNSH from the Scremerston, Yoredale, Millstone Grit formations and Cleveland Group (Figure 2).

Previous work has also highlighted the potential source rocks of this area. Collinson et al., (1995) documented the impact of facies variability of coals and mudstones of the northerly, deltaic Yoredale, Millstone Grit units with minor source potential, to the southerly, basinal mudstones and siltstones with a greater source rock potential, enhanced within marine bands. Shales and coals of the Scremerston Formation provided a rich source potential. Kerogen types were dominantly gas prone (Collinson et al., 1995). Hay et al. (2005) and Parsons (2015) also consider the Scremerston Formation a source rock. Dolan and Associates (1994) viewed the Scremerston Formation coals and Namurian coals as volumetrically important gas sources.

Analysis of new and legacy RockEval data (Vane et al., this study) identified a number of gas prone wells on the southern margin of the Mid North Sea High with good-excellent Carboniferous source rock potential in the Yoredale and Scremerston intervals (the lower–mid Carboniferous clastic play e.g. 42/10b- 2, 41/15- 1, 42/09- 1, 42/10a- 1) and variable levels of maturity ranging from oil to gas mature e.g. Figure 36.

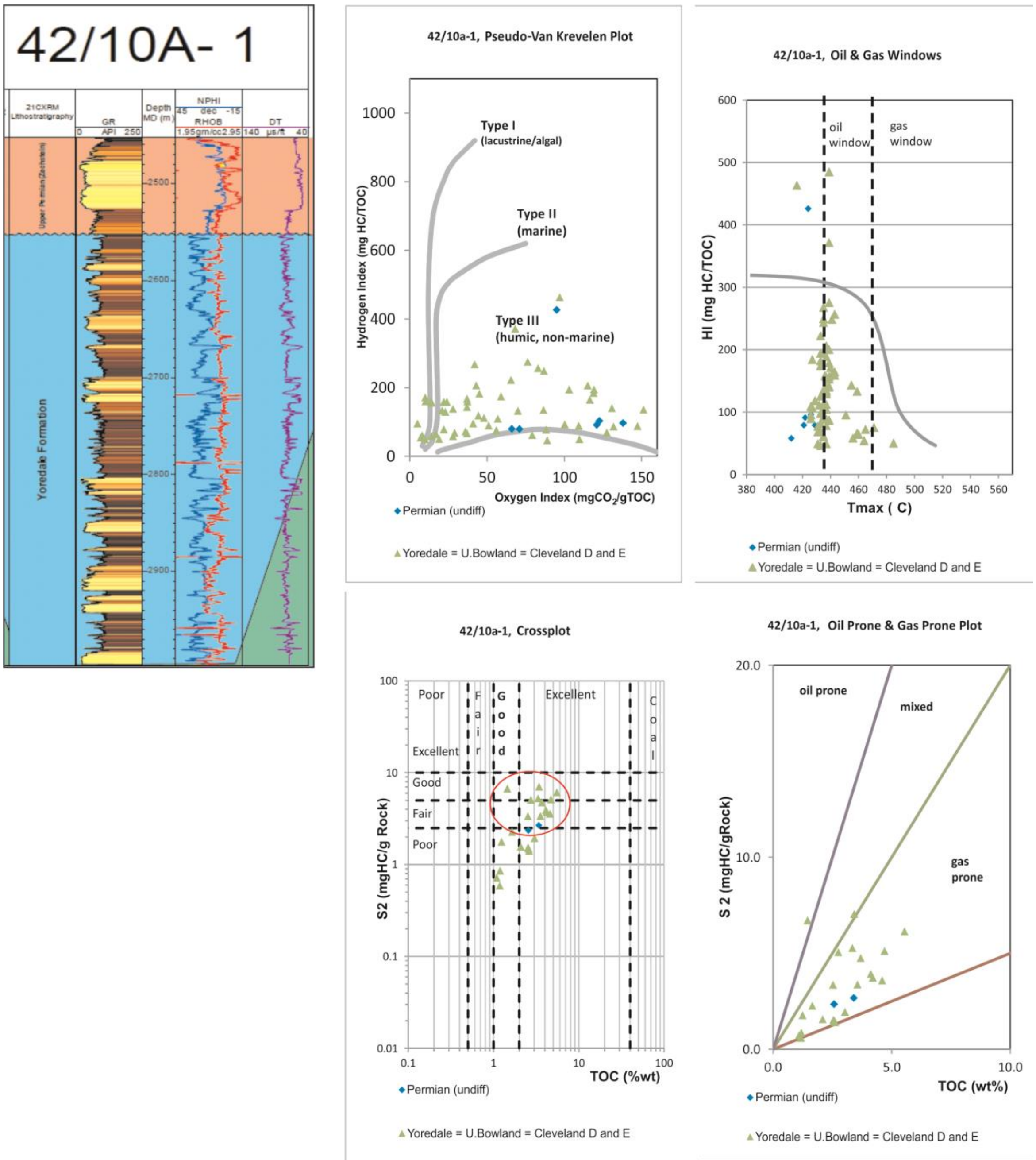


Figure 36 Example of source rock quality and maturity from a well within the lower–mid Carboniferous clastic play on the southern margin of the Mid North Sea High. The plots show source rocks within the Yoredale Formation that are largely gas prone, are oil to gas window maturity and range from poor to good quality potential.

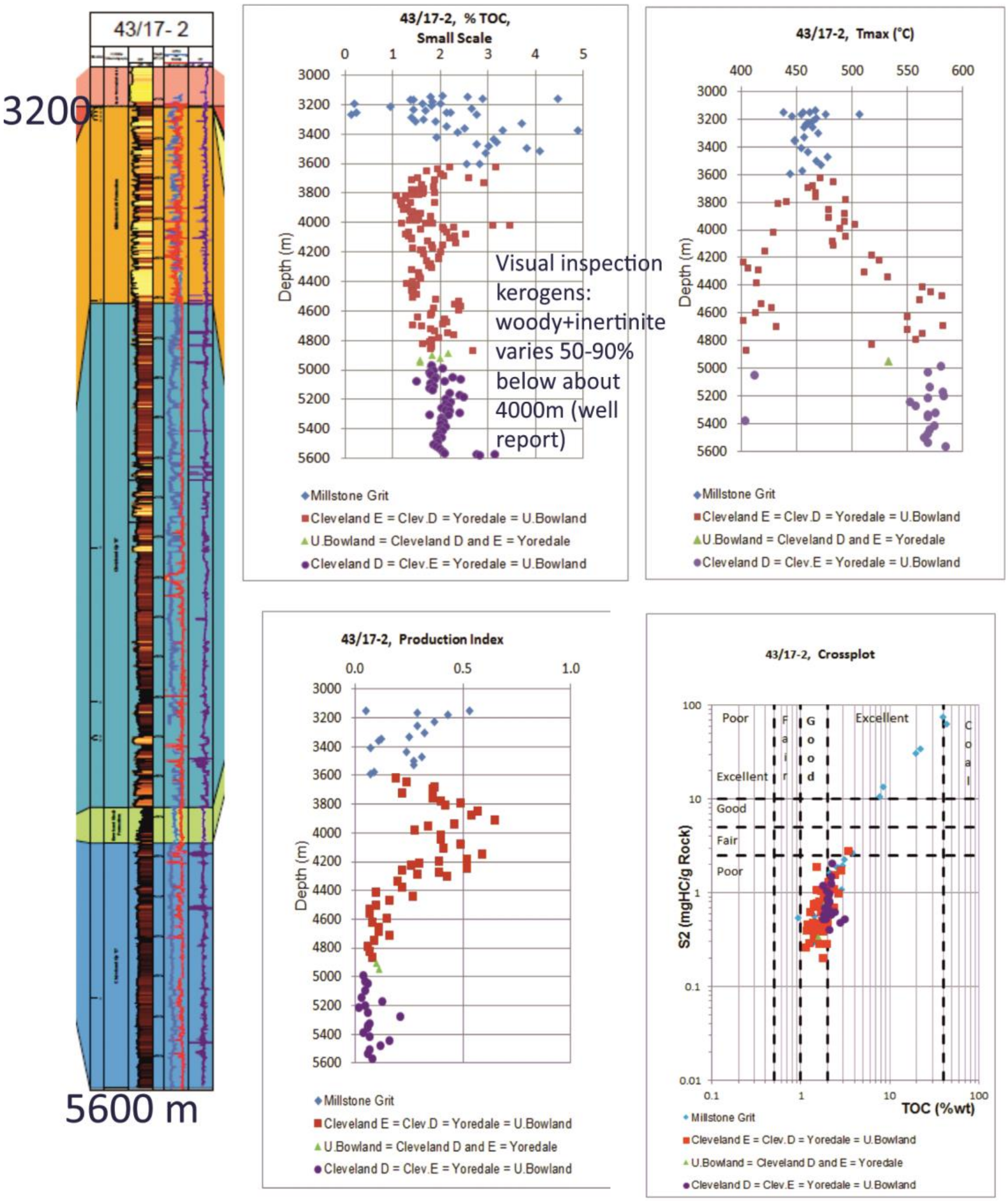


Figure 37 Example of source rock quality and maturity from a well within the lower–mid Carboniferous basinal play on the southern margin of the Mid North Sea High. The plots show source rocks within the Cleveland Group and Millstone Grit Formation.

Moving southwards to the basinal lower–mid Carboniferous play, a number of wells e.g. 41/14-1, 41/20- 1, 43/17- 2 have thick (up to c. 2 km proven) fair-excellent TOC rich sequences within the Cleveland Group that exhibit generally low S2 values (Figure 37). The source rocks vary from oil to gas mature, to overmature, suggesting some depletion could have occurred due to hydrocarbon generation. This is supported by peaks in S1 and PI (Figure 37) and by basin modelling work (below). A contributory factor to low S2 values is also the variable kerogen types within some intervals of the Cleveland Group that contain a large proportion of woody and inert kerogens (see Vane et al., this study). The characteristically high gamma unit of the Upper Bowland Shale is observed within the Cleveland Group. Kearsey et al. (this study) discuss the equivalence of these units to the onshore Bowland Shale Formation of the Craven Basin (Figure 38) and the Bowland-Hodder unit of Andrews (2013) that was estimated to contain a 1329 tcf (P50) shale gas resource in central-northern England (Andrews, 2013).

Figure 38 Example of the Upper Bowland Shale at outcrop, Quarry, Bleasdale Lancashire. BGS Photo P213491 BGS©NERC. All Rights Reserved 2016

In order to assess source rocks over the whole stratigraphical interval, petrophysical calculation of TOC contents based on the Passey method and calibrated using measured data was undertaken (Gent, this study). It showed the basinal Cleveland Group strata, with volume of clay >50% cut off applied, have average TOC contents between 1.5–3.4 weight (wt)%, with between 64–98% of the stratigraphic unit being comprised shale with TOC> 1 wt% (Gent, this study). Note that in some wells (e.g. 43/17- 2) the calculated thickness of Cleveland Group shale with TOC>1 wt % is over 1400 m (Gent, this study). Whilst particular units such as marine bands or the Upper Bowland Shale are particularly organic rich, it is also notable that there is a very thick succession of fair-good source rock quality.

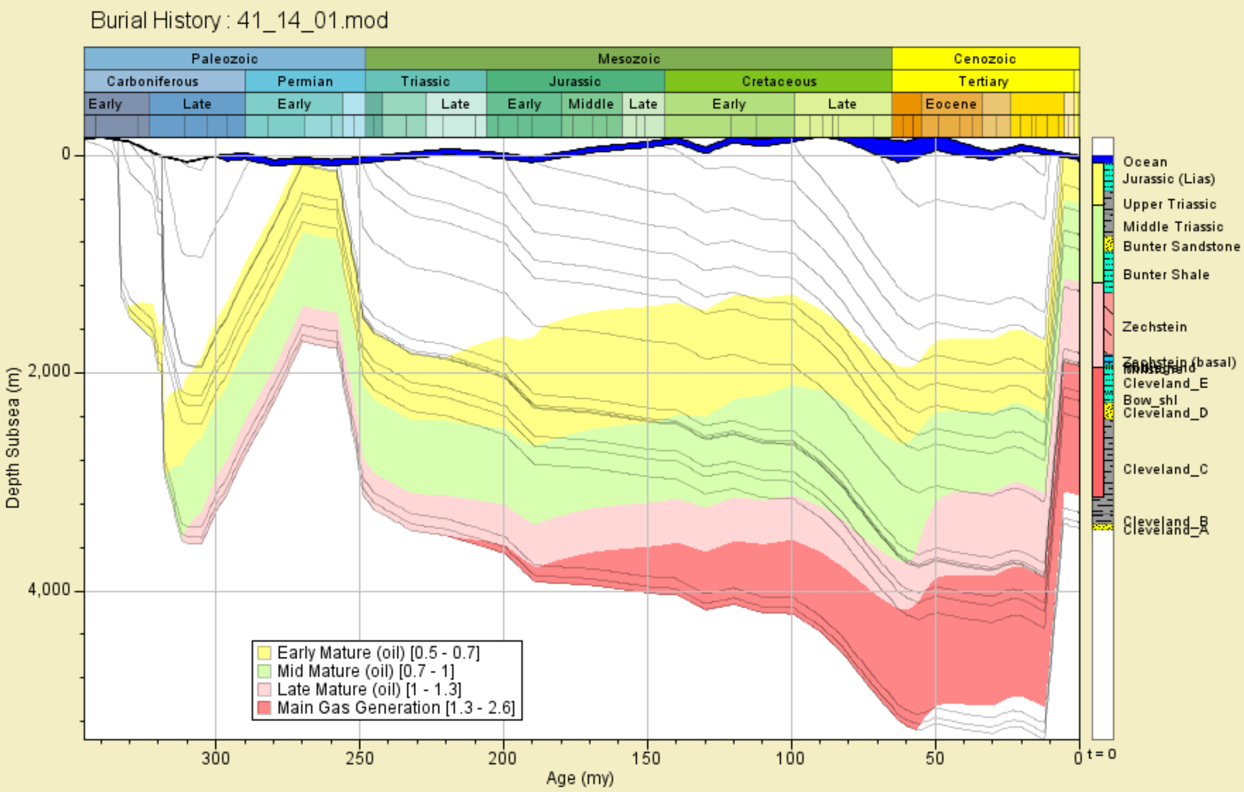
Coals were excluded from the petrophysical analysis but nevertheless, measurements from the Yoredale Formation clastic play on the southern margin of the Mid North Sea High indicate average TOC contents of shales between 1.8–3.4 wt% with 50–74% of the unit containing shale with TOC>1 wt% . Similar values were obtained for the Scremerston Formation of 34–65 % shale succession with average TOC 1.3–4.1 wt%. For the Millstone Grit Formation, 18–71 % of the unit was shale with average TOC varying from 1.4–2.7 wt % (Gent, this study). The clay rich intervals within these units are commonly tens of metres thick and calculated thickness of shale with TOC>1 wt % in the wells studied is commonly between 100 - 500 m (Gent, this study). The figures highlight variability within the Carboniferous succession. In some wells a large proportion of the strata are potential source rocks, both within the basinal shales of the Cleveland Group (including Bowland Shale) and the delta slope and top facies of the Scremerston, Yoredale and Millstone Grit formations. Some possible lateral variability was detected with the Cleveland Group in eastern Quadrant 43 having lower TOC wt% than in the western Quadrant 41 (Gent, this study).

In summary, source rock geochemical data indicate a number of stacked, good-excellent quality source rock intervals in the lower–mid Carboniferous clastic and basinal plays. Poorer source rock potential is observed overall in gas mature basinal wells, possibly resulting at least in part from depletion due to hydrocarbon generation.

5.2.4 Maturity, migration and charge

Collinson et al. (1995) undertook maturity modelling and identified a generative depocentre in the Carboniferous basinal shales of southern parts of Quadrants 42 and 43. Generation commenced in the late Carboniferous and continued until Cenozoic (Miocene or possible Palaeocene) uplift. In some 'basinal' wells e.g. Kirby Misperton and 43/17b- 2, the majority of gas generation was modelled in the late Carboniferous, before Varsican inversion and the development of traps, though it continued until Cenozoic uplift. Wells on the basin margins generated gas between Variscan-Cimmerian Orogenies whilst wells on the Mid North Sea High were largely immature for gas generation and mature for oil generation (Collinson et al., 1995). Lateral northwards migration and vertical migration into deltaic clastic deposits (Yoredale and Millstone Grit) was modelled, along with migration through Zechstein evaporites to Triassic reservoirs over a faulted margin (Collinson et al., 1995). Relinquishment reports have also documented modelled northward migration of hydrocarbons from the Silverpit Basin 'basinal play' towards Breagh (e.g. RWE Dea 2011a).

In this study, basin modelling was undertaken in three wells, 41/14- 1, 41/20- 1 and 43/17-2 situated offshore the Cleveland Basin in the lower–mid Carboniferous basinal play. All three wells indicate hydrocarbon generation in the late Carboniferous and Cenozoic from Cleveland Group (basinal Yoredale equivalent) and Millstone Grit Formation (Vincent, this study). The possibility of some Carboniferous depletion of gas-prone source rocks is clear in 41/14- 1 and 43/17-2, before traps and seals were in place (Figure 39).



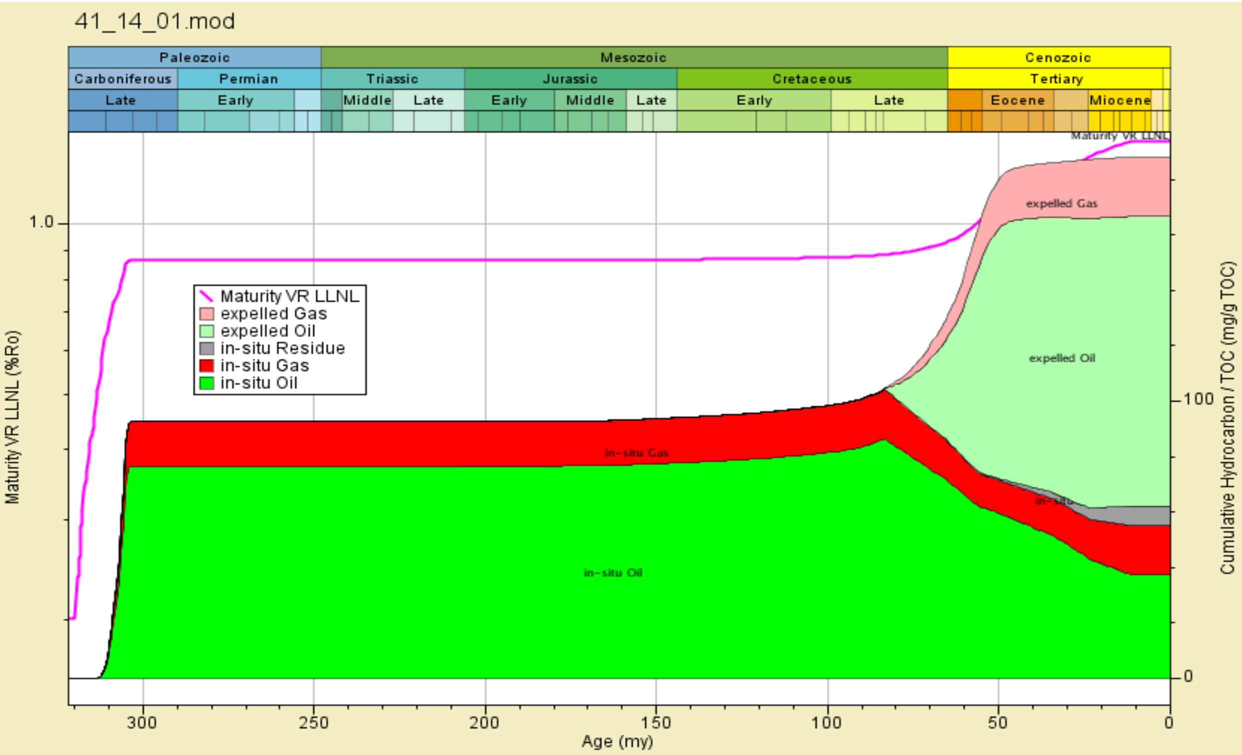


Figure 39 Thermal and burial history curve (above) for well 41/14- 1 from Vincent (this study). Generated hydrocarbons (below) time plot for Well 41/14-01 showing timing of generation for Cleveland E model layer. The current model suggests that generation started during the Carboniferous Period but expulsion of hydrocarbons only occurred during deepest burial during the Cenozoic Era.

In well 42/10b- 2 situated within the lower–mid Carboniferous clastic play, the lower maturity levels resulted in a burial history model of gas generation from Fell Sandstone-basal Scremerston interval during Cenozoic times when Zechstein and younger strata would have provided a seal (Vincent, this study). A relinquishment report for block 42/10 also suggests charge from Namurian/Dinantian strata (Wintershall, 2010).

The results of migration modelling, with oil and gas migration and generation in the central-southern Quadrants 42–44 are shown in section 2.2 above.

5.2.5 Reservoir rocks

Collinson and Jones (1997) examined in detail the nature and distribution of potential reservoir sand bodies along the southern margin of the Mid North Sea High using well and onshore analogue outcrops. The main potential reservoirs identified were major channel sand bodies: extensive in the Fell Sandstone Formation and more subtle, coarser-grained palaeovalley fills through the early Carboniferous and early Namurian. Transgressive quartzitic sandstones retaining permeability were considered important when combined with the high reservoir volume of a channel (Collinson and Jones, 1997). With the data available it was judged difficult to predict the stratigraphic or geographic position of sand bodies. In the Fell Sandstone Formation, reservoir volume and connectivity were not thought to be risks but a laterally extensive Carboniferous seal would be required apart from at base Perrmian Unconformity subcrop. Previous work was mentioned for Quads 43-49, which had shown that facies/grain size and maximum depth of burial both had a major influence on reservoir quality. Best potential reservoir quality was given in the northern part of Quadrants 41–44 and southern Quadrants 35-38 with <2900 m Carboniferous burial. (Collinson and Jones, 1997).

Blackbourn and Collinson (2006) document porosity development in Namurian-early Westphalian feldspathic sandstone in which most of the feldspar is altered to microporous kaolinite clay, providing a moderate porosity of 8-15% but commonly with limited permeability of < 1mD apart from in coarse sandstone. Quartzitic sandstones display permeabilities of 10’s mD but are usually fine grained, limiting reservoir potential. A type of low-kaolinite, high permeability sandstone reservoir was identified by Blackbourn and Collinson (2006) who suggested it was the result of dissolution by acids mobilised from underlying shales, with fluid movement along faults.

The sedimentology and spatial extent of channel sand bodies within the Scremerston and lower Yoredale formations were examined by Jones (2007). The largest stacked major channel systems (e.g. Figure 40) were up to about 27 m in thickness and up to 8km wide (Figure 41) with net to gross commonly > 0.8. Core data proved the best reservoir properties in stacked channel sandstones with the coarsest grain sizes having the best poro-perm values (Jones, 2007). Collinson (2005, his figure 8) proposed similar widths of sandstone-filled palaeovalleys and distributary channels across northern parts of Quadrants 41-43 in lower parts of the Yoredale Formation. Maynard and Dunay (1999) also give examples of the highest porosity (over 10%) and permeability (over 1 mD) within fluvial channel sandstones (their Figure 14). Symonds et al. (2015) also highlight the importance of sheet sandstones over a 17 km well correlation in and around the Breagh Field. Permeabilities of 0.1 – 100 mD were documented by Symonds (2015), who also notes that artificial stimulation of two Breagh wells has transformed their performance.

Figure 40 Multistorey channel sandstone forming the cliff at Marshall Meadows Bay, Berwick-upon-Tweed. The Dun Limestone (top of the Scremerston Formation) is present at the base of the cliff. Photo D. Millward.

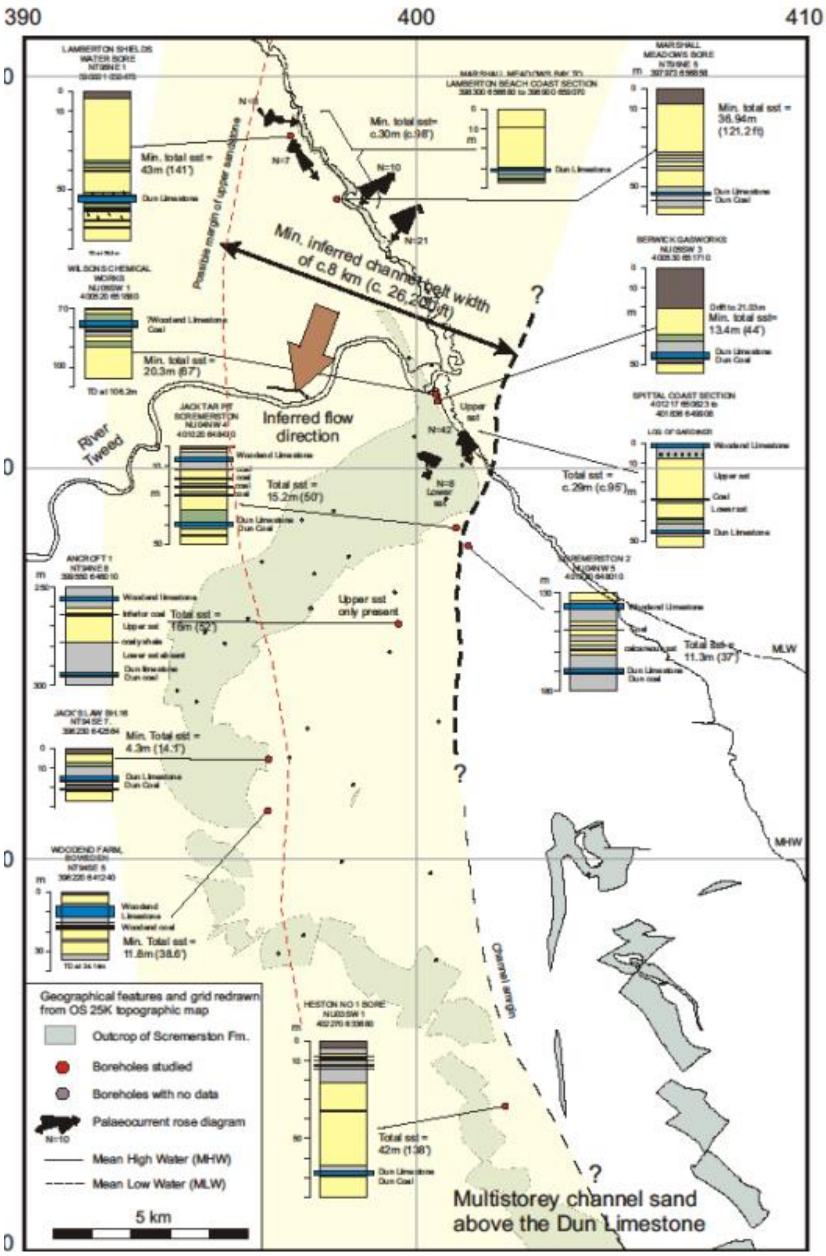


Figure 41 Schematic palaeogeography map showing the channel above the Dun Limestone, using outcrop and onshore borehole data, from Jones, 2007.

Onshore, Hampson (1997) studied younger, Namurian sand bodies related to turbidite-fronted deltas in a sequence stratigraphic framework. High relief erosion surfaces formed due to fluvial incision during relative sea level fall and sediment bypassed into the basin as sand-rich turbidite fans. During the transgressive systems tract, coarse-grained fluvial and deltaic sandstone bodies accumulated on the delta-plain (Hampson 1997, his Figure 15). A similar model may be applicable to the southern North Sea (Hampson et al., 1997). In this study, the independent examination of well data and construction of palaeogeographic maps has led to a similar position of the delta plain to basin as previous work by Collinson et al. (1995) and Collinson and Jones (1997). Though high resolution, sequence stratigraphic examination of offshore wells was not attempted in this study due to the lack of correlative chronostratigraphic data and the regional scale, the onshore work of Hampson (1997), Church and Gawthorpe (1994) and Jones and Chisholm (1997) appears highly relevant to the Visean–Namurian delta plain to basinal setting. It could be applied if chronostratigraphic constraints were improved. Integrated with the improved understanding of basin structure documented in this study (Arsenikos et al., this study), future work could apply similar techniques across Quadrants 41–44 to facilitate the prediction of reservoir sand bodies.

In this study, petrophysical work calibrated by measured data has shown the Fell Sandstone Formation to have favourable reservoir properties in terms of NTG and porosity. In the wells examined for the petrophysical study, it has a NTG varying from 0.34-0.82 with porosity ranging from 6-13 %. However the largest average estimated permeability is low at 0.4 mD (Hannis, this study). In contrast, core material from well 43/02- 1 has an average porosity of 13 % and average horizontal permeability of 18 mD. Maynard and Dunay (1999) recognised the reservoir potential of the Fell Sandstone Formation with NTG exceeding 70% and Hay et al. (2005) summarised porosities of 5-19 %.

Figure 42 Coarse-grained sandstone of the Fell Sandstone Formation, Northumberland BGS photo P709474. BGS©NERC. All Rights Reserved 2016.

The Fell Sandstone Formation is a clear candidate for a reservoir interval as it is predominantly comprised coarse-grained sandstone deposited by a major braided fluvial system (Figure 42). Onshore the Fell Sandstone Formation is an important aquifer supplying water for Berwick-upon-Tweed (Stone et al., 2010). Seven discrete sandstone aquifers are separated by thick, laterally persistent layers of impermeable mudstone and the majority of flow is from fractures or thin, coarse-grained layers (Stone et al. 2010). Onshore, the Fell Sandstone Formation is the reservoir interval in the Errington-1 well, which had limited gas shows maximum porosity of 6% (ROC Oil, 2005). Further data on core measured poro-perm and diagenesis of this interval are required for consideration as a petroleum reservoir at depth offshore.

In the petrophysical study, relatively large average porosities of up to 12% were also found in parts of the Yoredale Formation, and despite its NTG of up to 0.31, the net has relatively high estimated permeabilities, averaging 144.45 mD in one well. The Scremerston Formation largest average porosity is 12%, but it has a relatively low NTG of 0.24 (Hannis, this study). The time-equivalent units of the Cleveland Group have poorer NTG and porosity characteristics (Hannis, this study) as would be expected from their mudstone-dominated character.

The relatively low NTG in the Scremerston and Yoredale formations and variable but locally high poro-perm is compatible with the sedimentary facies of these units, where sandstones occur as thick incised valley fill, channels, sheet sandstones and a variety of other fluvial to marine settings.

The basinal Cleveland Group succession has potential for stratigraphic plays, intra Carboniferous structural plays and/or tight gas potential. Kearsey et al. (this study) describe these deposits as distal deposits shed of the Yoredale delta front; the sandstone and limestone units may be turbiditic. Sand bodies range from 5 to over 25 m in thickness and core logs donated by J. Collinson & C. Jones interpret a range of marine, delta slope, interdistributary channel and turbiditic deposits. One well, 43/21- 2, examined petrophysically for reservoir quality penetrated the Cleveland Group D, E and Bowland Shale and gave low estimated porosity and permeability (Hannis, this study; Table 2) and low measured core values (maximum porosity 2.2 %, permeability 0.01 mD). Further data collation and assessment of the quality and continuity of reservoir sand bodies is recommended. Cameron et al. (2005) noted that reservoir properties of turbidite mudstones interbedded with basinal mudstones were likely to be adversely affected by depth of burial, unless enhanced by early gas charge.

Many of the lower–mid Carboniferous intervals contain interbedded sandstones with poor-moderate reservoir properties. Measured core data suggests an overall decrease in poro-perm with increasing depth (Figure 16). This study has given a regional overview of potential reservoirs; however more detailed, local work is required on reservoir facies, extents and diagenesis within the lower–mid Carboniferous clastic and basinal plays.

5.2.6 Seal rocks

The primary seal on the southern side of the MNSH is the Permian Silverpit mudstone and/or Zechstein evaporites. Generally these form an effective regional seal. However faults occasionally cut the Zechstein, salt movement has created some thinned zones and carbonates replace evaporites in some locations. Some relinquishment reports contain a risk of effective sealing e.g. 42/18 (RWE Dea, 2011)

If effective, intraformational Carboniferous seals could be very important both in the clastic and basinal plays of the southern MNSH margin. Though a Carboniferous intraformational seal is not documented, the Trent Field produces from a Namurian reservoir shown at some distance below a higher Westphalian A reservoir (O'Mara et al., 2003), implying an intra-Carboniferous seal is in place. The Boulton Field reservoirs are separated by an intra Carboniferous seal (Conway and Valvatne, 2003). Onshore UK there are examples in the West Firsby and Welton fields of intraformational Carboniferous seals where pro-delta mudstones overlie marine bands in deltaic cyclothems (Kombrink et al., 2010). The Saltfleetby field is a good example of successful entrapment of gas beneath Westphalian A mudstone-dominated strata (Cameron et al., 2005). Pharaoh et al. (2011) document intraformational seals and traps more generally in the East Midlands oil and gas fields. The Errington-1 well demonstrates the Scremerston Formation (equivalent) seal of the Fell Sandstone Formation (ROC Oil, 2005 and T. Parsons *pers.comm.*). Collinson and Jones (1997) identify a mudstone unit within the Yoredale Formation of Quadrant 41 as a credible Carboniferous seal overlying significant channel sand bodies. They discuss the potential for reservoir-seal pairs in more basinal settings of the southern Quadrants 41–43 but state that intra Carboniferous seals on the 'northern margin'(northernmost Quadrants) 41–43 are virtually non-existent and that base-Permian closures would be prudent.

5.2.7 Traps

A variety of structural (faulted and folded) and dip/unconformity traps can be interpreted from seismic sections, primarily at the base Permian unconformity (Figure 43). Intra-Carboniferous seals would give opportunity for stacked structural traps and stratigraphic traps are possible for isolated channel sand bodies (Figure 43). A variety of these trapping styles are documented in relinquishment reports.

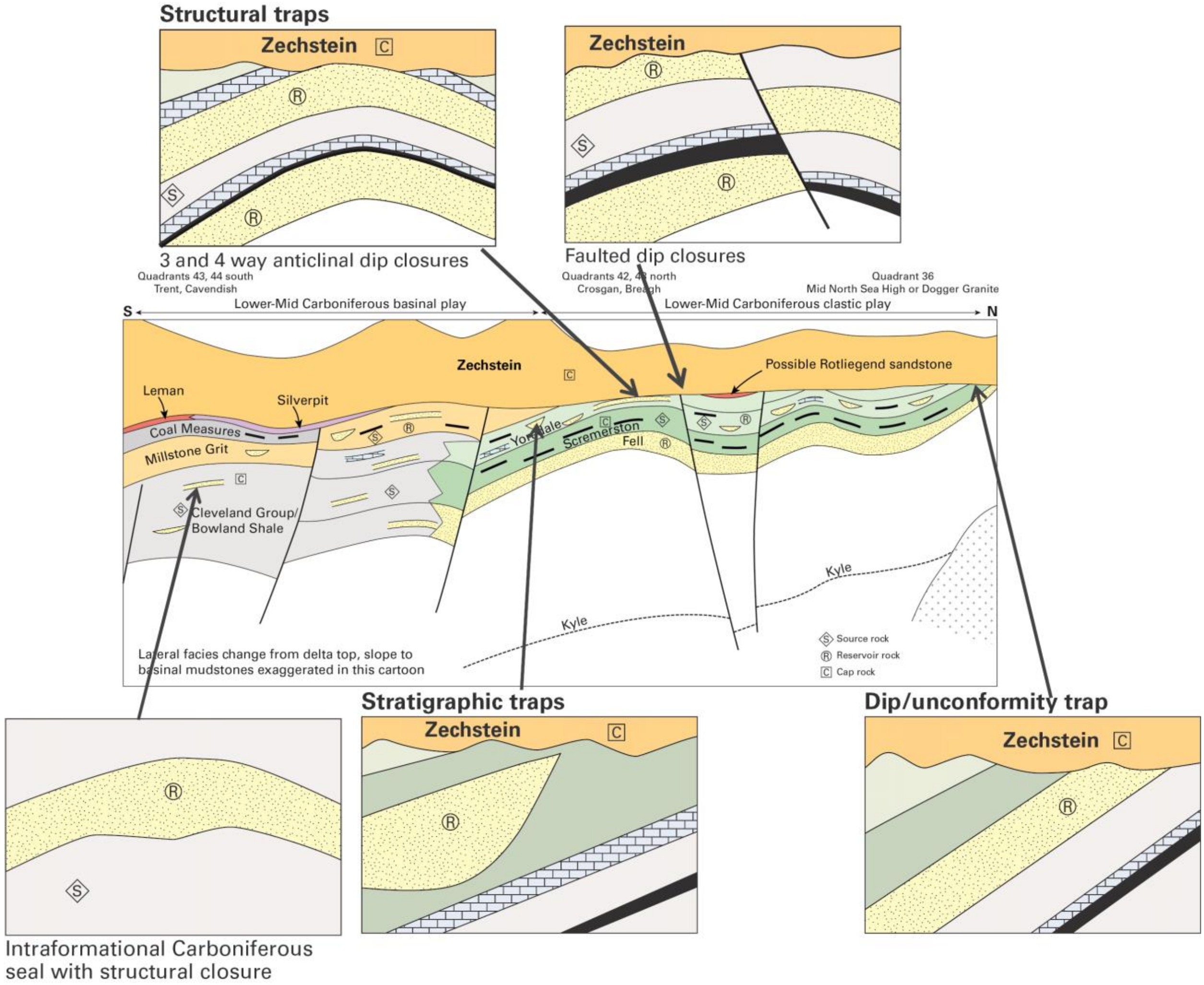


Figure 43 Summary of trap styles observed or envisaged on the southern MNSH margin.

5.2.8 Knowns and Risks

All the elements of a working petroleum system are in place on the southern margin of the MNSH but there is a great deal of local variability. Source rock studies have proven a gas prone, gas mature lower–mid Carboniferous sequence in the south of the area, largely coincident with mudstone- and siltstone-dominated basinal play (Figure 44). Basin modelling indicates northwards migration from this kitchen area (Figure 44). In the northern parts of Quadrants 41–44 some gas prone wells in the lower–mid Carboniferous clastic play are gas mature and with good–excellent source rock quality, others are within oil window maturity. Multistorey channel sandstones form proven reservoirs with dip and faulted closures against the base Permian unconformity and Zechstein evaporite seal.

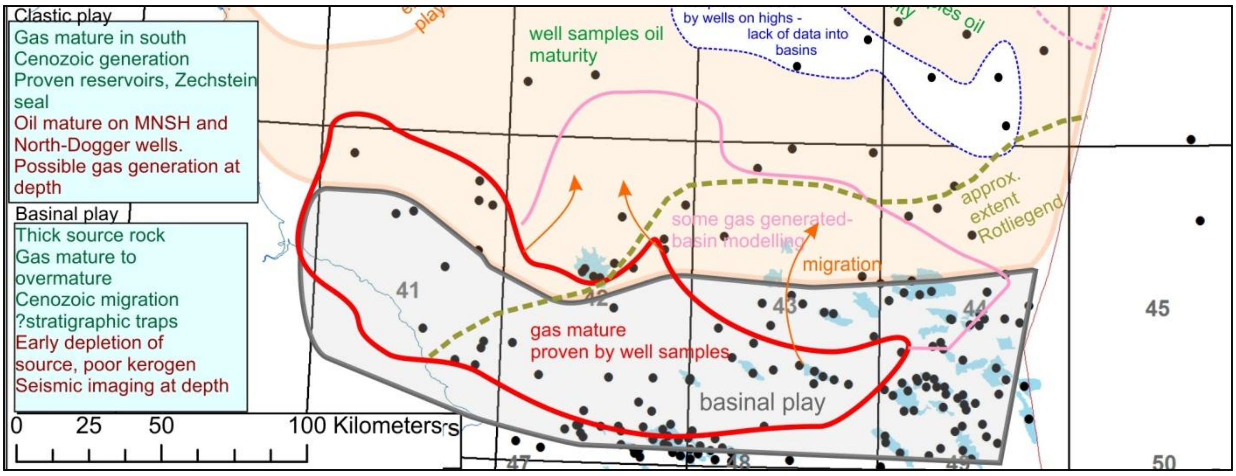


Figure 44 Summary map of knowns and risks on the southern MNSH margin.

Petroleum generation and preservation in the late Carboniferous and Cenozoic are the two main critical elements (Figure 45).

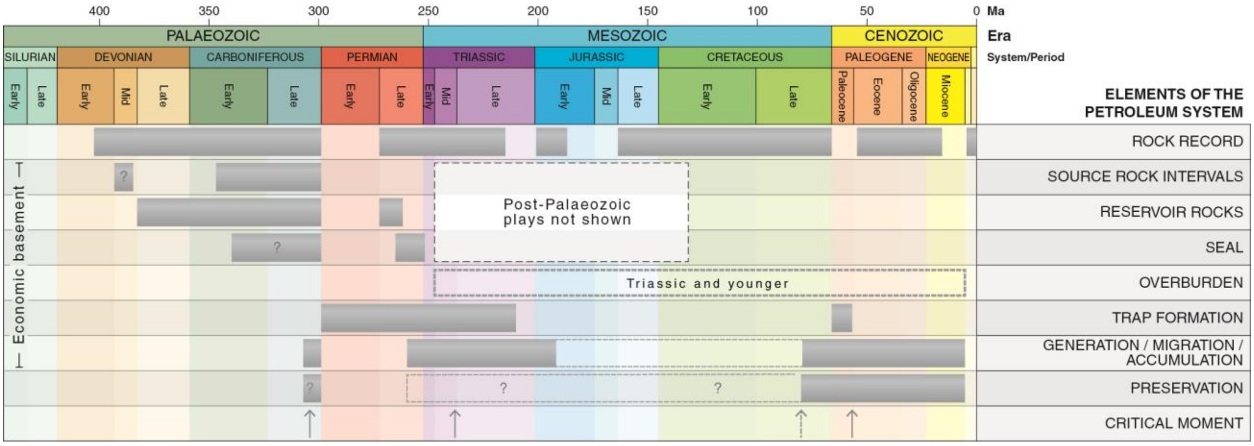


Figure 45 Critical elements summary for the southern margin of the Mid North Sea High. The Mesozoic–Cenozoic timing of generation varies dependent on location, with an Eocene phase of generation widely observed in basin modelling studies (e.g. Vincent, this study).

Risks for the lower–mid Carboniferous plays along the southern MNSH margin from this study and relinquishment reports include:

- The northward existence and maturity of source rock intervals
- Lateral variability in source rock quality related to basin configurations e.g. basins in which the mudstone-siltstone dominated succession accumulated are poorly imaged on seismic towards Cleveland Basin
- Late Carboniferous maturation and depletion of source rocks, before traps in place
- Poor and variable reservoir quality either in Rotliegend or Carboniferous
- Many of the largest structures may have already been assessed or drilled. Structures remaining could be relatively small. However they could offer reservoirs at multiple depths.
- Limited knowledge of the effectiveness of intra-Carboniferous Seals

A particular lesson noted from several relinquishment reports in this area is that due to the variability of the overburden, depth conversion is critical to give accurate structural maps (i.e. structures interpreted in time can disappear on depth conversion).

5.3 NORTH DOGGER BASIN - QUADRANT 29 BASIN - WEST CENTRAL SHELF

5.3.1 Overview

A Lower Carboniferous basin interpreted to contain Scremerston Formation source rocks was mapped from seismic data in the southern part of Quadrant 29 by Hay et al. (2005). There are however, no proven Carboniferous well penetrations in this area. Seismic and gravity interpretations by Milton-Worssell et al. (2010, their Figure 4) illustrated the continuation of this basin to the south-east into Quadrants 38 and 39, lying between highs of the Auk-Flora ridge and Farne Block (containing the Dogger and Farne granites). Situated outside the area of Jurassic source rock, Hay et al. (2005) noted the correlation between the occurrence of gas chimneys and shallow gas in southern Quadrant 29 with the mapped basin, and suggested a deep thermogenic source for the gas. Maturity and basin modelling were undertaken and predicted maturation and migration of gas from a Lower Carboniferous source (Hay et al., 2005, Figure 46).

Seismic interpretation observed gas chimneys in this area, however it was not clear whether these were sourced at Palaeozoic levels or not (S. Arsenikos, *pers. comm.*). A donated PA resources report describes well 29/19-2 as the only known well in the area with shallow gas, in a Pliocene sandstone. The gas has high levels of methane which was interpreted as suggestive of a biogenic rather than thermogenic origin (PA Resources, 2011). No source typing analysis appreas to have been performed.

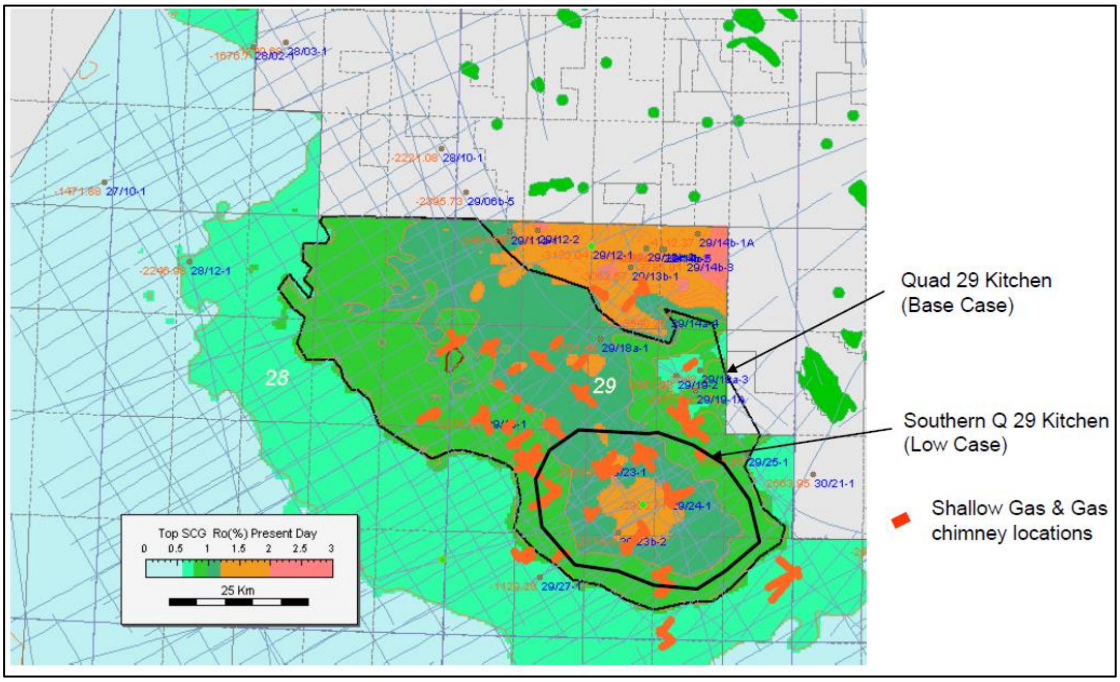


Figure 46 Plot of modelled Top Scremerston Formation maturity in Quadrant 29 and location of seismically mapped shallow gas and gas chimneys from Hay et al. (2005).

In this study, a Devonian–lower Carboniferous ‘North Dogger basin’ up to c. 7 km thick is mapped in Quadrants 38 and 39 (Arsenikos et al. this study, Kimbell and Williamson, this study). Wells 38/18- 1, 38/16- 1 and 39/07- 1 drilled at the basin margins prove source rock bearing Scremerston and Yoredale formations up to 590 m in thickness. These horizons are mapped to depth in the basin (Figures 28, 30, 47).

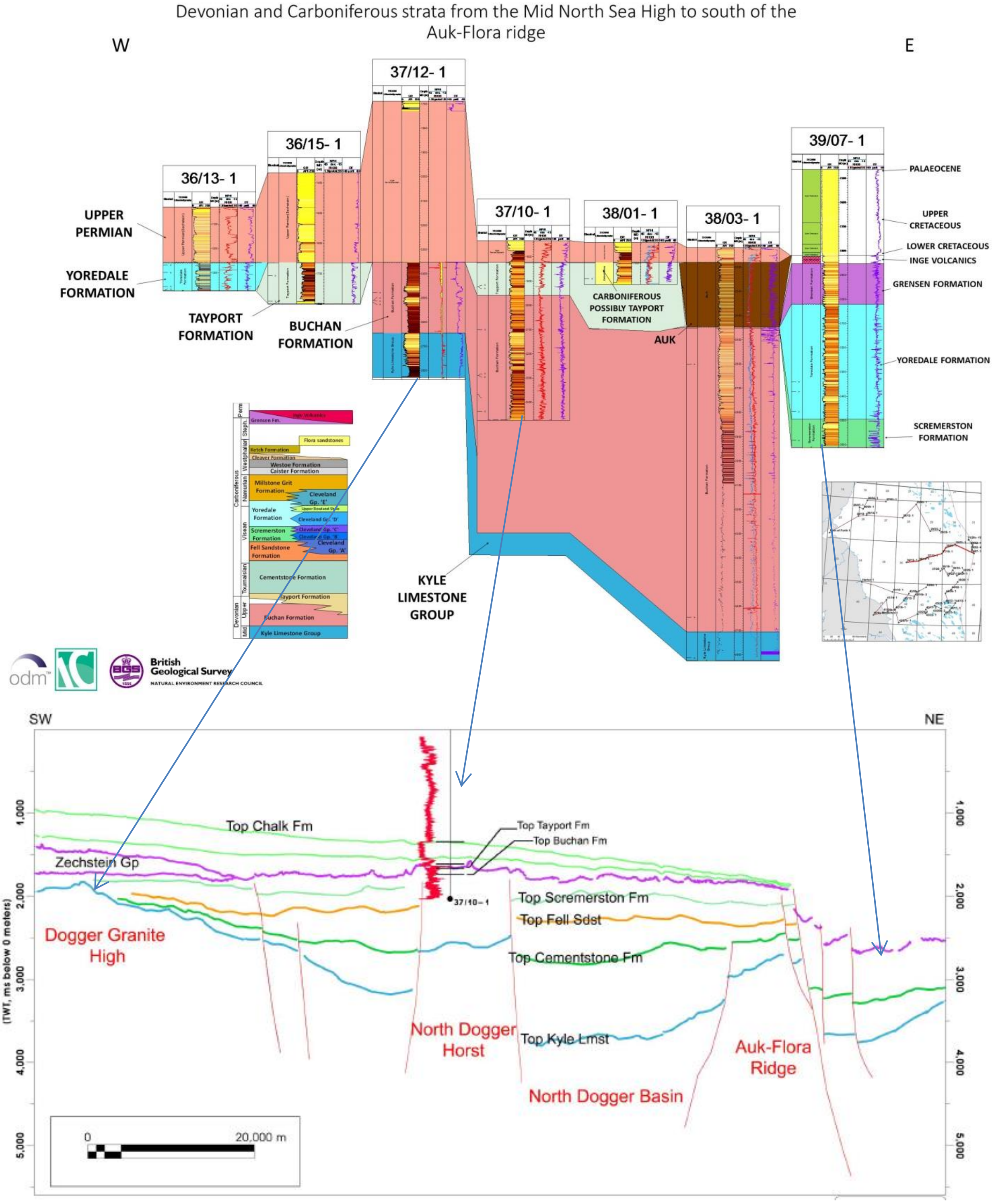


Figure 47 Well correlation panel and line drawing of approximately coincident seismic interpretation illustrating the mid-upper Devonian strata at the margins, or on faulted highs, in and around the North Dogger Basin (37/12- 1, 37/10- 1, 38/03- 1) and short penetrations of source rock bearing lower Carboniferous Scremerston and Yoredale formations at the basin margins e.g. 38/16- 1.

A shallower zone comprised of several faulted blocks is mapped on north-east (top Scremerston) and north-north-west (top Kyle) trends between Quadrants 30, 37 and 38 (Figures 28, 29), constrained by wells 37/10-1 and 38/03- 1. The ‘Quadrant 29 basin’ lies to the north-west and extends into Quadrant 28. No wells prove the Scremerston Formation but a characteristic package of seismic reflectors is present and the horizon is tied to the wells at significant distances from their location in Quadrants 38.

In the Dutch sector, the Elbow Spit granite and an interpreted Carboniferous basin to the north (EBN, 2015b) form the continuation of the Dogger Granite-North Dogger Basin. Wells in the Dutch sector on the northern side of the Elbow Spit high e.g. A16-1, A14-1 contain Yoredale to Millstone Grit formation strata (Kombrink et al., 2010). The Scremerston Formation with coals is proven in wells Gert 2 and Gert 3 in the Danish sector and the Yoredale equivalent is proven in the Gert -2 and Den P-1 wells (Bruce and Stemmerik, 2003).

In summary, the petroleum system of the North Dogger and Quadrant 29 basins is part of the lower–mid Carboniferous clastic play, underlain by potential lower Carboniferous–upper Devonian reservoir rocks and the possible mid Devonian play of the Kyle Group (see right hand side of Figure 4 above).

5.3.2 Fields, shows, discoveries

In addition to the shallow gas/gas chimneys mapped seismically in southern Quadrant 29, indirect indications of a working Carboniferous petroleum system are given by gas shows in 38/16- 1 and poor oil shows in 39/07- 1 (Amoco Petroleum, 1967; Hay et al., 2005; Figure 46 above). Other wells drilled on regional highs in Quadrants 37, 38, 39 have been dry.

Several wells in Quad 29 have oil shows in the Auk sandstone (Rotliegend, 29/20-1, 29/18-1 (weak gas shows), 29/23-1, 29/25-1) or Zechstein (29/20-1) (PA Resources, 2011). Geochemical typing of wells in this area has shown oil from 29/20-1 to be from an early mature Carboniferous (Scremerston Formation and oil shales) lacustrine (not Devonian) source using biomarker analysis (PA Resources, 2009). Isotopic signatures on shows and inclusions in Farris et al. (2012) were attributed to a Carboniferous coal prone source in 29/10-3st1.

In the adjacent Dutch sector, gas and oil shows are present in wells e.g. A14-01, A16-01 north of the Elbow Spit high and distant from a Jurassic source (EBN 2015a).

5.3.3 Source rocks

The top Scremerston Formation is interpreted on seismic to extend over much of the North Dogger and Quadrant 29 basins, along with a relatively thin interval of overlying Yoredale Formation (Figures 4, 24, 25). Well penetrations are only available in Quadrants 38 and 39. Source rock quality for the Scremerston Formation is judged to be excellent in 38/18- 1 and gas-prone with some oil prone intervals (Vane et al., this study and spreadsheet of geochemical data). In 39/07- 1 (Figure 48), there are significant thicknesses of coal recorded in the Scremerston Formation.

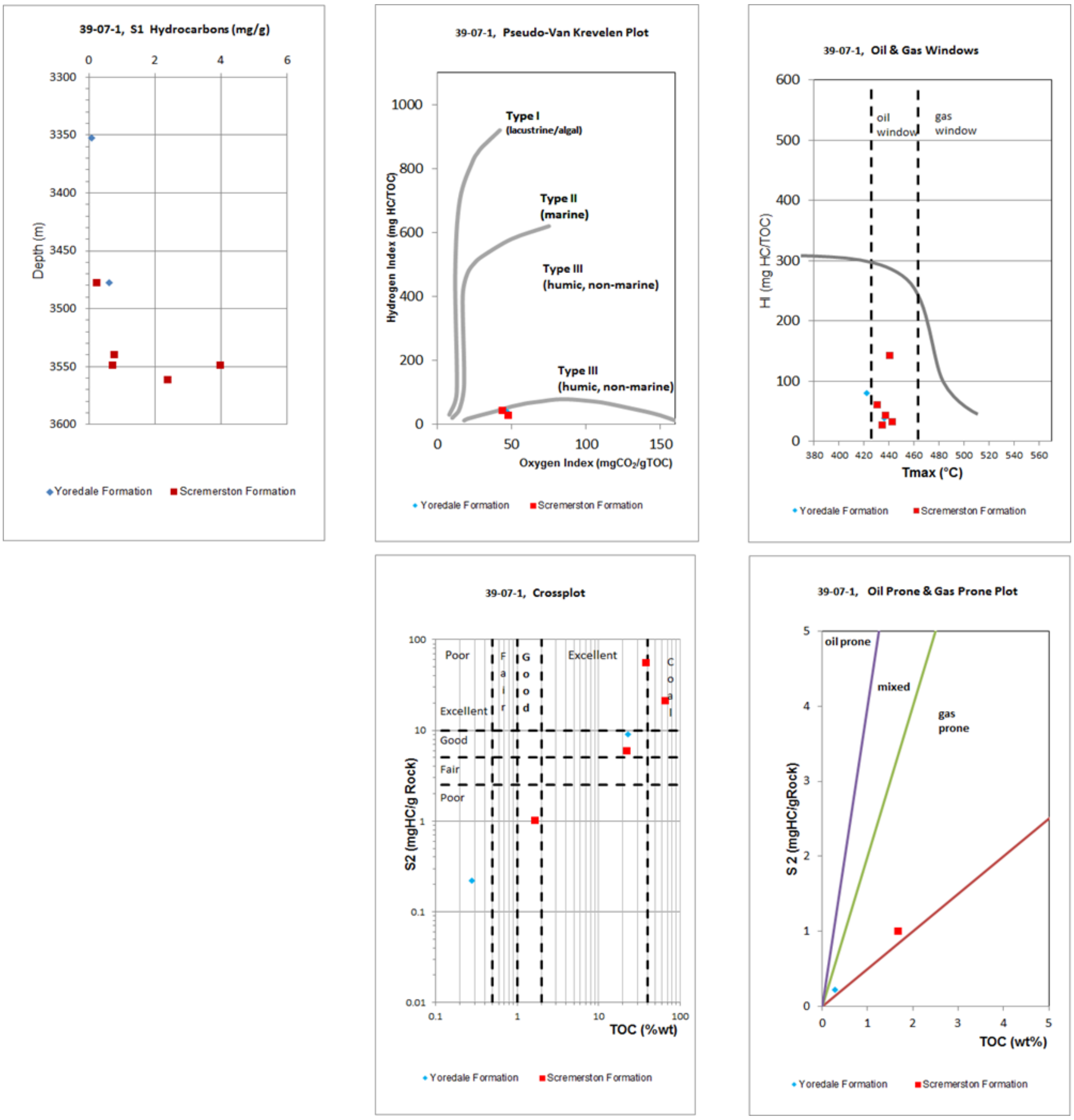


Figure 48 Selection of geochemical plots for the Yoredale and Scremerston formations in 39/07- 1 indicating gas prone source rocks with poor-good source rock potential, plus coals, all at oil window maturity.

Well 38/03-1 penetrated the mid–upper Devonian succession. Source rock quality was interpreted as poor (Vane et al., this study). Previous work has discussed whether thin coals are proven in the upper Devonian of this well or whether there was contamination of cuttings (Schroot et al., 2006, page 51, favouring the latter). Examples of this data are shown in section 6.1.3 below.

Petrophysical calculation of TOC content in the Yoredale Formation of 39/07- 1 gave an average TOC contents of shales between 1.1 wt% with 37 % of the unit containing shale with TOC> 1 wt%. Three wells in the Scremerston Formation (38/16- 1, 38/18- 1, 39/07- 1) gave average calculated TOC of 1.4-2.5 wt% with 20-39 % of the succession being shale >1 wt% TOC (equates to <50 m shale; Gent, this study). Based on the very limited well penetrations, lower Carboniferous successions in the North Dogger Basin appear less shale and organic rich than those in Quadrants 41-43. However they do contain significant coals that are excluded from the petrophysical analysis, meaning that the present source rock assessment is probably pessimistic.

5.3.4 Maturity, migration and charge

Maturity values in the wells drilled around the margins of the North Dogger basin are indicative of oil window maturity at Scremerston and/or Yoredale Formation source rock level (Figure 24, 25, 48). In the Dutch sector (blocks A, E) adjacent to Quadrants 39 the top pre-Permian strata reach oil and gas window maturity (Pletsch et al., 2010, EBN pers.comm.). The source rock is generally gas-prone with some oil-prone intervals, coals within the Scremerston Formation being of particular interest.

As no wells penetrate the basin centres, maturity modelling was undertaken for various ‘scenarios’ for wells 38/18- 1 and 29/27- 1 (Vincent, this study). Any available data was used, along with seismically interpreted depths to Devonian and Carboniferous horizons. Parameters were changed to examine how much burial would be required to enable gas maturity. The results for well 29/27- 1 were that a well drilled to Scremerston Formation level would be predicted to be at oil window maturity (Figure 49a). An additional 3.5 km of Carboniferous burial would be required to place the Scremerston Formation in the gas window (Figure 49b, Vincent, this study). Seismic mapping shows the top Scremerston at the position of 29/27- 01 to be at -3250 m, the deepest base Scremerston Formation in the Quadrant 29 basin is at -4500 m. The simplistic burial modelling does not therefore predict the Scremerston Formation is likely to reach the gas window in Quadrant 29. However the basin modelling is constrained by little data and the confidence in the model is low.

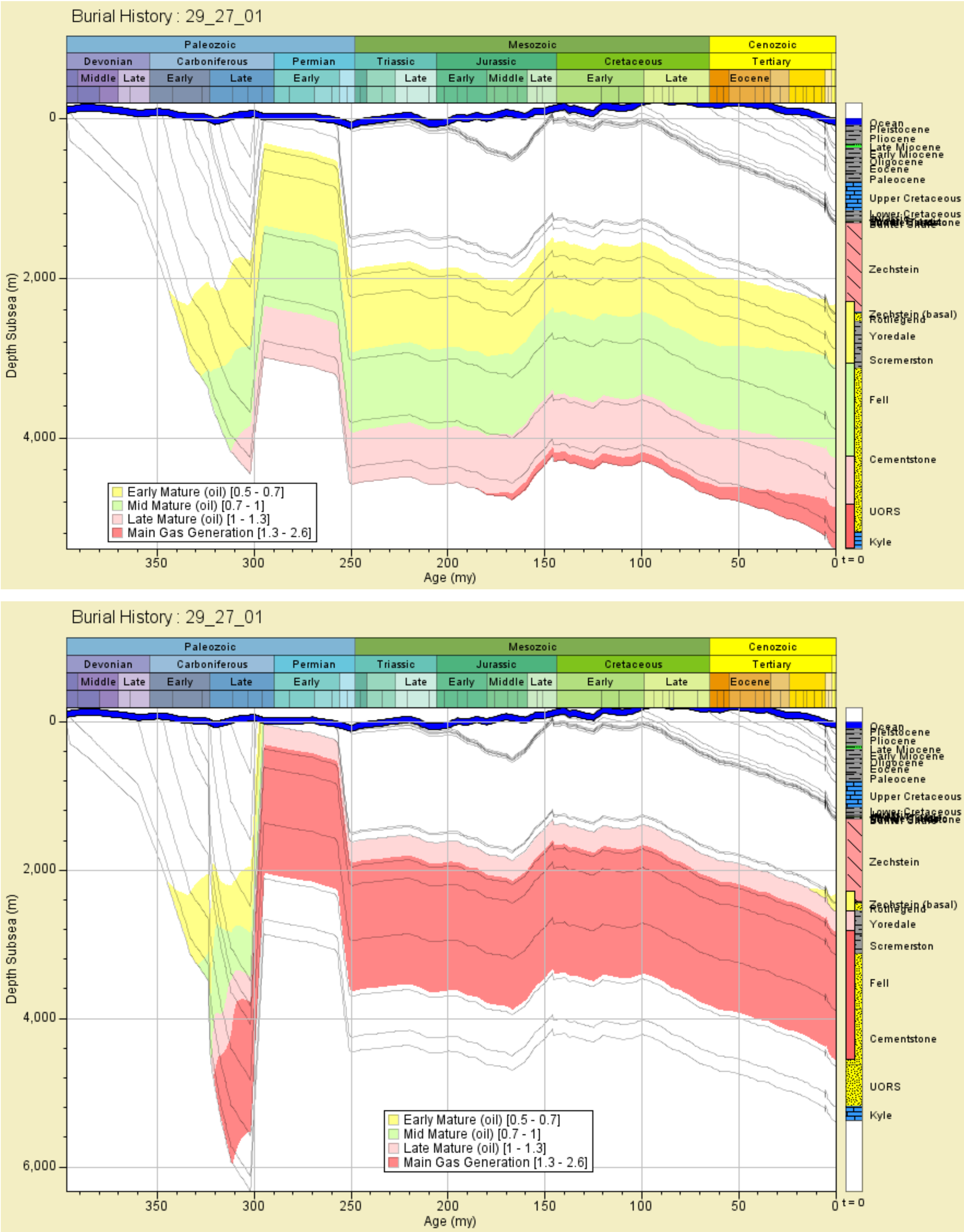


Figure 49 Basin modelling scenarios for well 29/27- 1 a) using well stratigraphy to the Zechstein, Carboniferous and Devonian estimated well tops from seismic mapping b) assuming 3 km additional Carboniferous burial to force the Scremerston source rock to the gas window

The results of this modelling appear to contrast with those of Hay (2005) who predicted gas generation and migration from the deepest parts of the Quadrant 29 basin (see Figure 46). However on close examination, pseudo wells that were predicted to enter the gas window had Carboniferous rocks to around 5 km depth (pseudo well #1 to VR=3) or 6 km (pseudo well #4, VR to 2.5; Hay et al. 2005 their Figures 6.17, 6.20). Wells with Carboniferous rocks at shallower depths e.g. 3.7 km depth (pseudo well #2 to VR=1.2) were within oil window maturity. A relinquishment report from southern Quadrant 29 (ConocoPhillips, 2011) predicted Early Carboniferous coals and shales to be mature for gas generation with charge occurring when seal and trap were in place. A donated report (PA Resources, 2009) predicted oil generation for well 29/20-1 but the bulk of generation occurring before Late Permian times and this lacking Cretaceous and Cenozoic burial and charge.

The scenario well 38/18- 1 was constrained by limited amounts of measured data in the good-excellent source rock quality, oil and gas prone Scremerston and Fell Sandstone formations. It was modelled as oil window maturity (Vincent, this study). An additional 3.5 km of Carboniferous burial was modelled to be required to facilitate gas window maturity. In the deepest parts of the North Dogger Basin the base of the Scremerston Formation is mapped as approximately 1.6 km deeper than in 38/18- 1 (Arsenikos et al., this study). Based on the current data/assumptions and low confidence scenario model the Scremerston Formation would not be gas mature in the basin centre.

In previous work, in blocks 38/20 to 39/21 the Carboniferous was interpreted as attenuated and was not thought to be deeply buried enough for gas maturity (Centrica, 2010)

In summary, maturity levels at basin margins, likely burial depths in basin centres and oil shows in overlying Permian strata provide evidence that the North Dogger and Quadrant 29 basins have been, or are, oil generative. However the volume and timing of generation is uncertain. In the basin centres, some basin modelling studies have predicted gas generative potential, others have not, highlighting the lack of data and low confidence of ‘scenario’ or ‘pseudo’ models.

5.3.5 Reservoir rocks

The limited well dataset suggests a similar clastic dominated palaeogeography to the Fell Sandstone, Scremerston and Yoredale formations on the southern margin of the MNSH (Figure 23). Reservoir potential can be envisaged in channel sandstones and sand sheets within the heterolithic succession. No measured core data was available for Carboniferous strata in this area, Devonian reservoir intervals are described in section 6.1.5 below.

Petrophysical work has shown the Yoredale Formation to have average porosity of 13% and NTG of 0.26 in 39/07-1. Values for the Scremerston Formation include an average porosity of 15% and NTG of 0.49 in 38/18- 1 as well as thin, 20% porosity unit of Fell Sandstone Formation. The Tayport and Buchan formations show an average calculated porosity of up to 13% and NTG of 0.73 in 37/10- 1, though average measured core values are lower at around 6% (Hannis, this study).

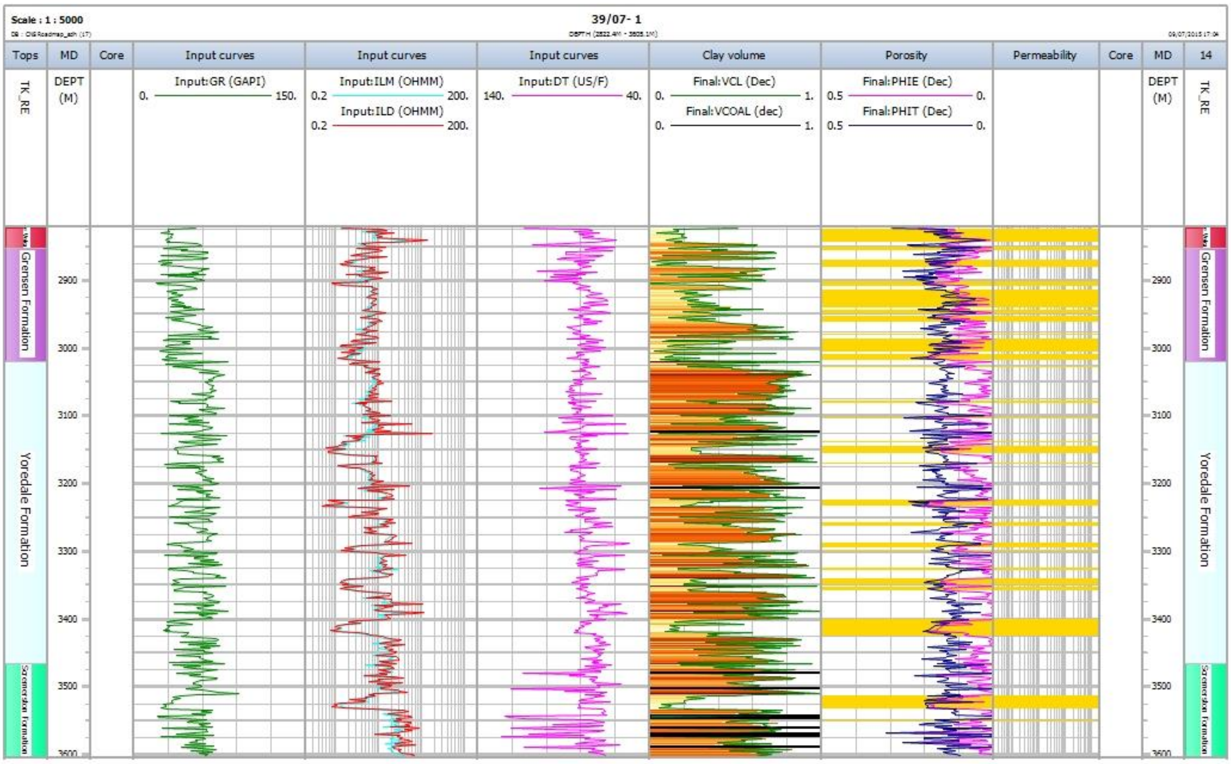


Figure 50 Image of petrophysical results for 39/07- 1 showing the presence of discrete sandstone intervals within the Yoredale and Scremerston formations and thicker sandstone intervals in the latest Carboniferous Grensen Formation.

Where present, Rotliegend (Auk Formation) sandstones could form a good potential reservoir. Hay et al. (2005) predicted migration to a Rotliegend reservoir in Quadrant 29. However to the south of the North Dogger and Quadrant 29 basins the Rotliegend is largely absent (Figure 17).

5.3.6 Seal rocks

From the very limited data, the existence of extensive mudstones that could act as intra-Devonian or Carboniferous seals is unclear. Zechstein evaporites offer the most obvious potential seal, though they are thin in northern Q38/39 (Figure 19) and Zechstein carbonates form a reservoir in Quadrant 30.

5.3.7 Traps

Seismic mapping indicates a variety of possible fold and fault geometry traps. Various prospects are described in relinquishment reports e.g. ‘Snizort’, a large faulted horst block (ConocoPhillips, 2010).

5.3.8 Knowns and risks

The North Dogger and Quadrant 29 basins are constrained by limited data but that data gives hints that a Carboniferous play could be active. Well and seismic interpretations for this study concur with previous work (Hay et al., 2005, Milton-Worssell et al., 2010) that a coal-bearing lower Carboniferous succession can be picked on seismic over much of this area. Wells at the margins of the North Dogger basin prove oil window maturity, good quality coal-bearing source rocks of the lower–mid Carboniferous clastic play, with interbedded or underlying potential sandstone reservoir units. The largely gas prone source rocks are more deeply buried within the basins such that higher maturity is expected in basin centres. Some units are oil prone and oil mature in wells at the basin margins. A Zechstein seal is present over much of the area. The majority of wells have been dry but 38/16- 1 well has gas shows and 39/07- 1 has poor oil shows and there are Carboniferous sourced oil shows present in the Permian of southern Quadrant 29.

Palaeozoic-sourced shows are present in the Dutch sector, along strike. Shallow gas and gas chimneys in southern Quadrant 29 may indicate a gas mature Palaeozoic source.

The critical elements summary (Figure 51) attempts to highlight the uncertainty as to whether Carboniferous source rocks are buried deeply enough in the Cenozoic to generate and preserve hydrocarbons from a dominantly gas prone source rock and/or whether there are enough oil prone source rocks to generate viable quantities of oil.

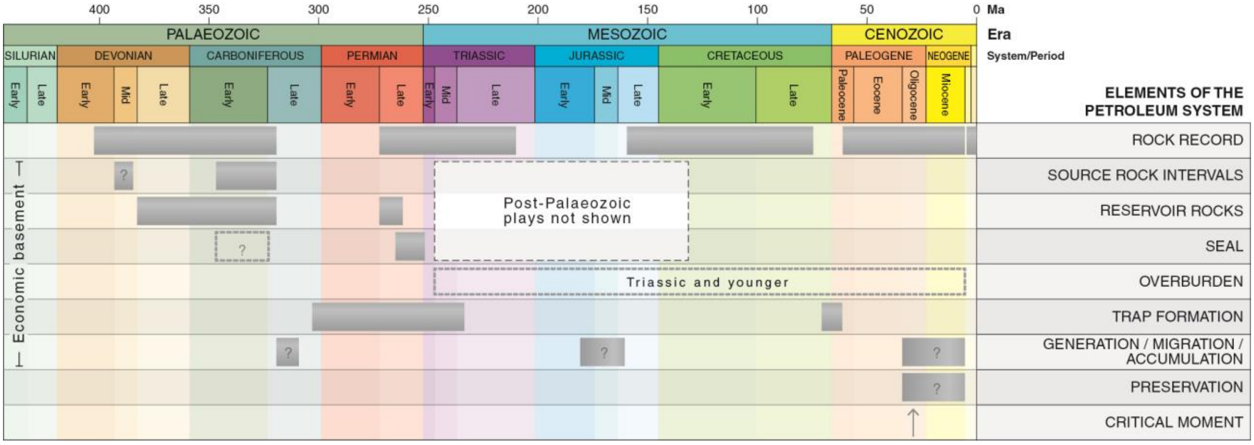


Figure 51 Critical elements summary for the North Dogger and Quadrant 29 basins. Note that the timing of generation is uncertain.

Thus, one of the key risks to a petroleum play within the lower–mid Carboniferous clastic system of the North Dogger and Quadrant 29 basins is the existence of a mature source rock. No wells have been drilled deep enough to prove the Carboniferous source rocks in Quadrant 29. Further study of wells drilled around the basin margins would be beneficial to see if they were valid tests. Various trap styles are likely to be present but reservoir and seal quality are poorly known.

5.4 DEVONIAN-CARBONIFEROUS MID NORTH SEA HIGH

5.4.1 Overview

The lower–mid Carboniferous clastic play system is interpreted to occur across the south and south-east of the Mid North Sea High area, underlain by lower Carboniferous-upper Devonian possible reservoir intervals and the mid Devonian Kyle Group in the east (Figure 68 below). Well data is very sparse and seismic and gravity interpretation indicates granite-cored and basement highs, with intervening, relatively thin Carboniferous basins and terrace/platform areas (Figure 52. Kimbell and Williamson, this study; Arsenikos et al., this study). The Top Cementstone Formation (near base Carboniferous) is interpreted at depths of 3500 m in the south of Quadrant 36, rising to depths of 750 m close to the coast in northern Quadrant 34. The long-lived high of the Dogger granite block in Quadrants 37 and 38 forms a major regional structure. The north-west end of the block is marked by the steep, north-east trending Western Arcuate Fault System (Arsenikos et al., this study).

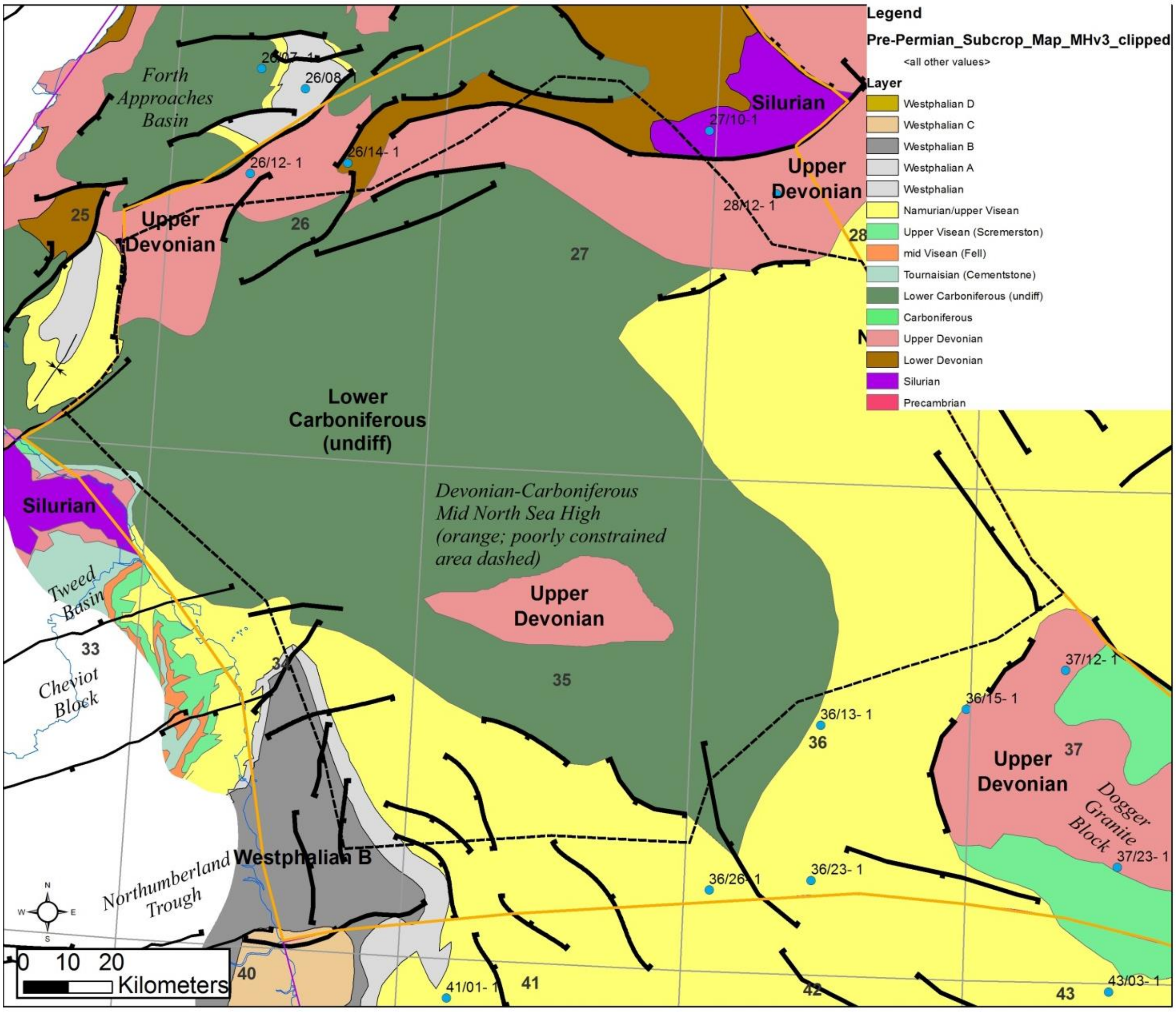


Figure 52 Pre-Permian subcrop map over the Mid North Sea High highlighting the lack of well data and extensive upper Devonian, lower Carboniferous (undifferentiated) and lower–mid Carboniferous Yoredale/Millstone Grit (yellow) intervals.

Onshore to near offshore the Northumberland Trough and Alston Block (south-west Quadrant 35 and north-west Quadrant 40, Figure 52) Coal Measures strata are at subcrop in the area adjacent to the Mid North Sea High. Carboniferous source rocks are believed to present onshore, but are thought to have attained maximum, oil window maturity in late Carboniferous times before trap formation, or be overmature due to intrusion of the Whin Sill (Chadwick et al., 1995). Various options for reservoir rocks exist but are not predictable with the current data set. There are a variety of structural traps and possibilities for intraformational cap rocks (Chadwick et al., 1995). In this study, poor 2D seismic data quality and lack of well ties resulted in only the top Cementstone Formation being interpreted in and around the offshore Northumberland Trough, to depths of 2750 m (Arsenikos et al., this study). The east-north-east trending block and basin structure mapped onshore to offshore changes to north-westerly trending faults in the vicinity of the Coal Measures outlier. Wells to the south in Quadrant 41 are gas mature and have gas shows (Vane et al., this study, Vincent, this study). Thus offshore southern Quadrant 34, thick Carboniferous sequences up to Westphalian Coal Measures offer an untested Carboniferous play that is distinctly different from the lower Carboniferous–upper Devonian Mid North Sea High to the east and north.

5.4.2 Fields, shows, discoveries

No shows have been recorded in the 3 wells in Quadrant 36, or in wells on the Dogger granite block in Quadrant 37. Dead oil staining was recorded in the Zechstein of 36/15-1 (Hay et al. 2005). In the adjacent onshore Northumberland-Solway basin, oil shows have been recorded in the Archerbeck and Becklees boreholes, with gas commonly occurring in mine workings in the area and in small quantities in many boreholes (Chadwick et al., 1995, ROC Oil, 2005). There are however no discoveries or fields onshore or offshore this area.

5.4.3 Source rocks

The source rock potential of the Yoredale Formation across northern parts of Quadrant 36 is judged to be good to excellent and mainly gas-prone with some oil prone intervals (Figure 53, Vane et al., this study). Wells in Quadrant 37 penetrate the lower Carboniferous-upper Devonian possible reservoir intervals and the Kyle Group and have poor source rock potential (Vane et al., this study, wells 38/22- 1, 37/12- 1; see section 6 below).

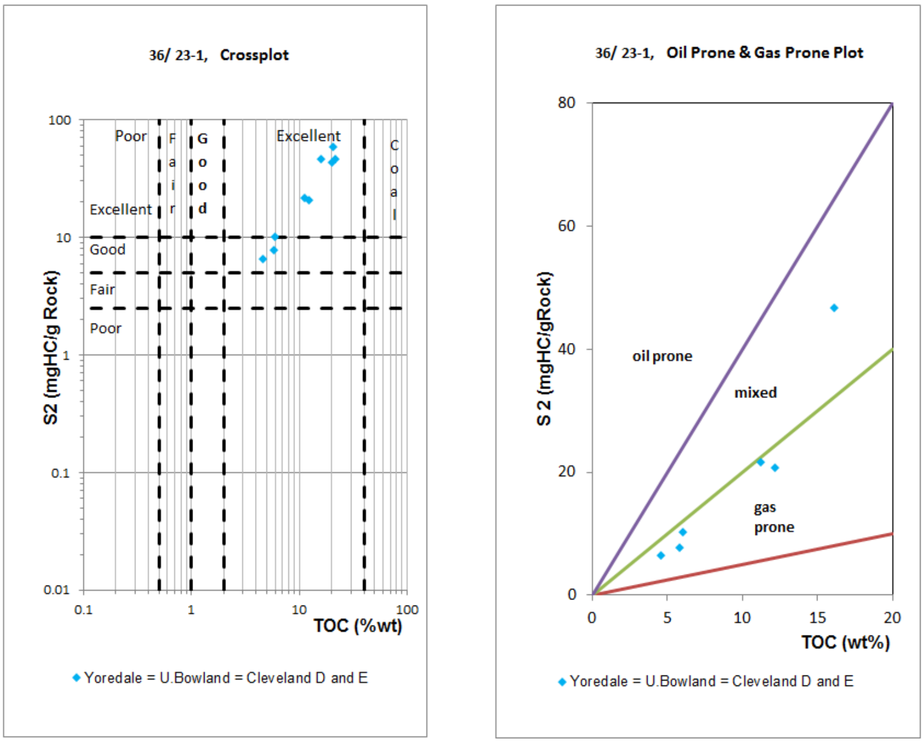


Figure 53 Example of good–excellent source rock quality data for largely gas-prone samples from the Yoredale Formation of Quadrant 36.

Petrophysical calculation of TOC content in the Yoredale Formation from 36/13- 1 gave an average of shales of 2 wt% TOC with 37 % of the unit containing shale with TOC> 1wt%. Coals are present but were excluded from the petrophysical analysis, meaning that the present source rock assessment is probably pessimistic. No other stratigraphic units were penetrated.

5.4.4 Maturity, migration and charge

Basin modelling of 36/13- 1 indicates early oil maturity was reached in late Carboniferous times followed by Variscan and Mesozoic uplift and further Cenozoic burial. A similar model but reaching mid oil maturity levels is interpreted for 36/23- 1, 35 km to the south (Figure 54). Given the wells are judged to be largely gas prone little or no petroleum generation is modelled, with maximum burial in late Carboniferous times.

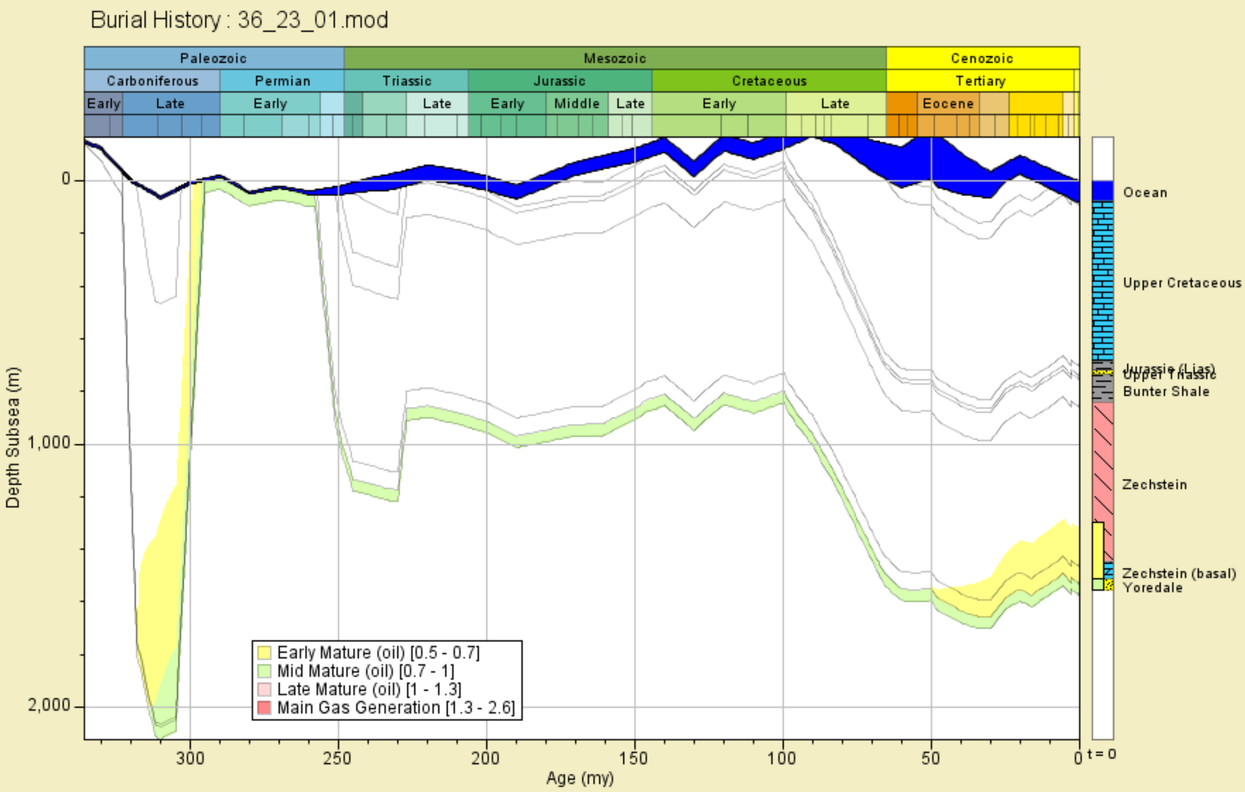


Figure 54 Basin modelling history for 36/23-01 showing the Yoredale Formation reaching mid maturity for oil generation

Any putative petroleum system on the MNSH would be reliant on long-range, up-dip migration of hydrocarbon sourced from surrounding areas of deeper Carboniferous burial. Though many caveats must be appreciated, basin modelling indicates that if long range migration took place there are regional base Zechstein highs of interest in the MNSH area (Figures 13, 14). The offshore Northumberland Trough area is likely to have a different maturity history but is currently unconstrained by data.

5.4.5 Reservoir rocks

No measured core data on reservoir properties was available for the Scremerston or Yoredale formations. By analogy to areas further south, it is expected that channel systems of reasonable reservoir quality would exist within lower–mid Carboniferous sequences such as the Yoredale Formation. The lower Carboniferous-upper Devonian Tayport and Buchan formations (and lateral equivalents) are widespread but very little data is available (see Section 6).

Petrophysical work has shown the Yoredale Formation to have a calculated average porosity of 19% and NTG of 0.43 in 36/13- 1 (Hannis, this study). The Buchan Formation in 37/12- 1 appeared to be a poor reservoir with NTG of zero and an average calculated porosity of 6% (Hannis, this study).

Due to the area being a topographic high dividing the Northern and Southern Permian basins, Rotliegend sandstones are largely absent over the Mid North Sea High (Figure 17), though ongoing work is investigating local deposits.

5.4.6 Seal rocks

No data is available to assess possibilities for intra-Devonian or intra-Carboniferous seals. The Zechstein Group is present over the Mid North Sea High but thick evaporitic sequences are not present everywhere due to development of carbonate facies and halokinesis.

5.4.7 Traps

Various possibilities for structural and dip traps can be seen on widely spaced 2D seismic but cannot be defined in three dimensions.

5.4.8 Knowns and risks

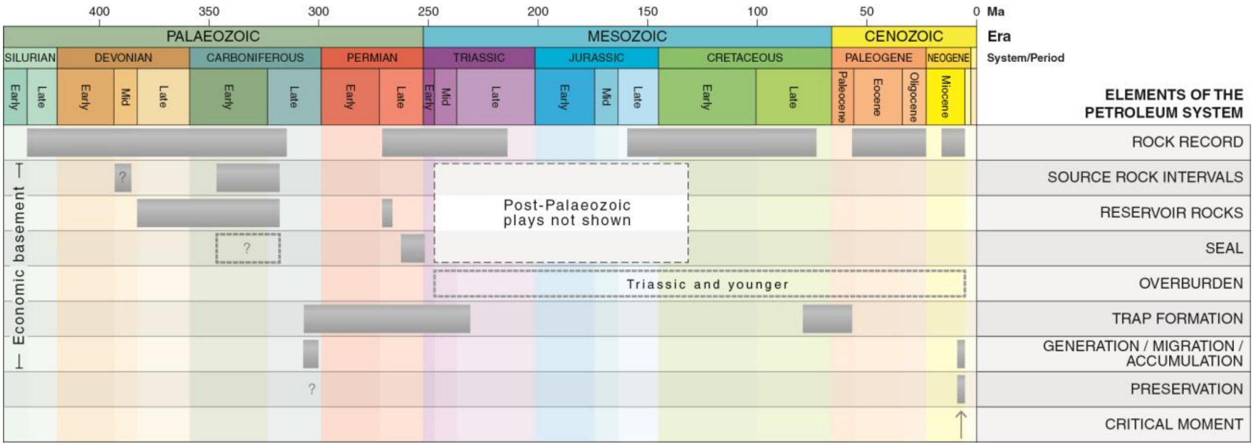


Figure 55 Critical elements summary for the Mid North Sea High. Generation of oil in the Cenozoic is tentative.

Lack of data upon which to base interpretations is the main risk across much of the Mid North Sea High area. Gas prone source rocks are interpreted to be present across some parts of the area but with relatively low, oil window maturities such that basin modelling does not indicate gas generation in the wells studied (Figure 54). Increased maturity could exist in deeper parts of basins not yet well defined by seismic mapping but indicated in the gravity study (Kimbell and Williamson, this study, Figure 56). The offshore extension of the Northumberland Trough is one such area. On the very limited data available, some large parts of the Mid North Sea High are lacking evidence for a Devonian–Carboniferous source rock. However there is the possibility of coal, mudstone or oil-shale deposited in isolated basins between widely spaced seismic lines, or in long range migration of hydrocarbon from adjacent, deep basins. Potential upper Devonian–lower Carboniferous reservoir rocks are likely to be extensive but little is known of their reservoir quality.

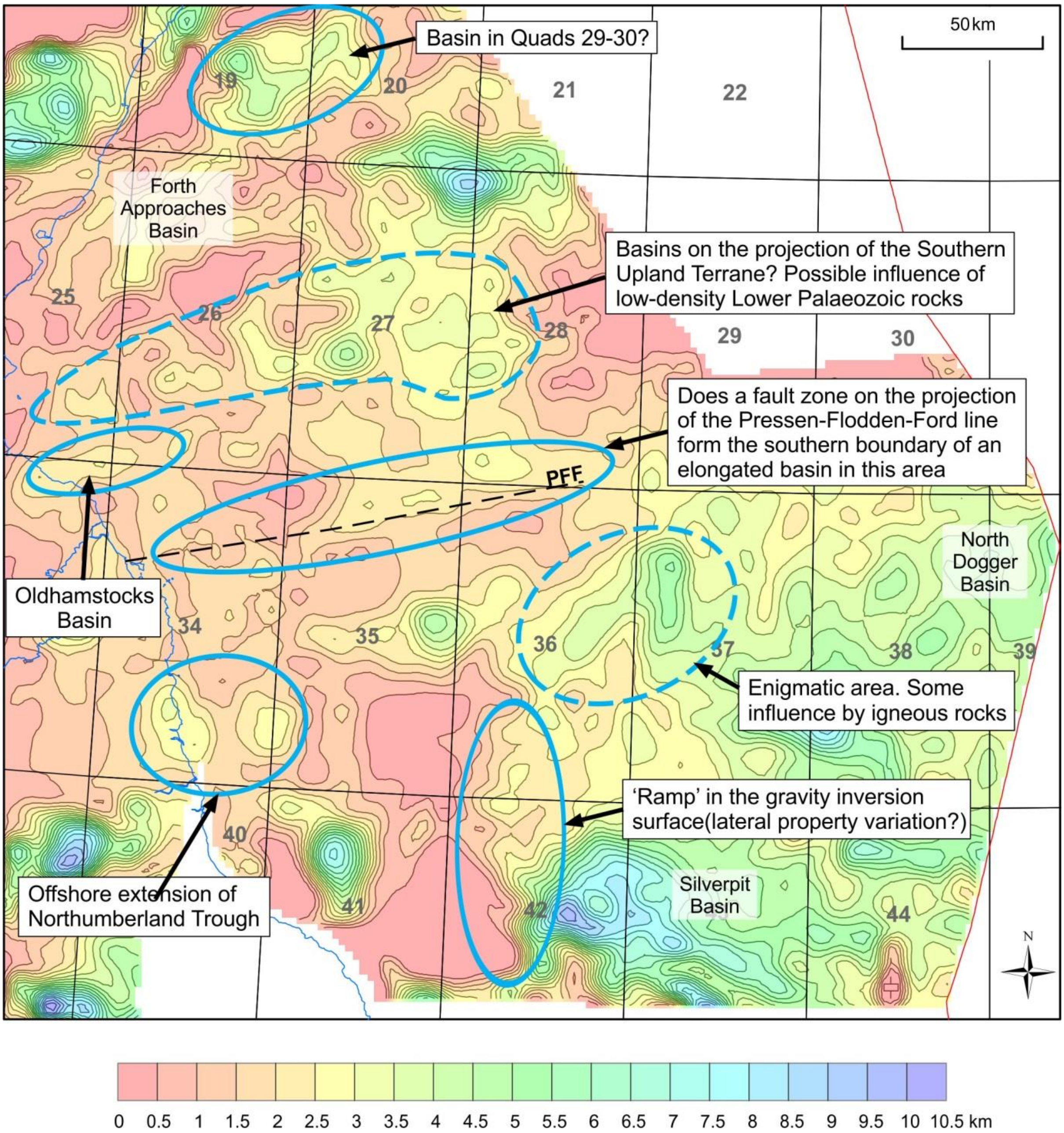


Figure 56 Contour map of thickness between base Zechstein and gravity inversion surface annotated with targets for further investigation, mainly areas of possible sedimentary thickening not resolved or poorly imaged in the initial seismic database.

Gravity modelling indicated some areas of sedimentary thickening to be investigated further (Kimbell and Williamson, this study, Figure 56). The 2015 Government-funded seismic data will provide further valuable insight into the geology of Devonian–Carboniferous Mid North Sea High.

5.5 AUK-FLORA RIDGE

5.5.1 Overview

The Auk-Flora ridge, a WNW-ESE trending pre-Devonian high in Quadrants 30 and 31 (Milton-Worssell et al., 2010), hosts the Auk, Argyll (renamed Ardmore and now Alma) and Flora fields as well as numerous other post-Palaeozoic fields. It is proven by geochemical typing that the fields are sourced from upper Jurassic mudstones (Kimmeridge clay) of the Central Graben (see Figure 11; Marshall and Hewett, 2003; Hall, 1997; Hayward et al. 2003). Devonian (Auk, Argyll) or Carboniferous (Flora, Westphalian sandstone) reservoirs occur in faulted blocks up-dip from the Jurassic source, with Cenozoic migration (Figure 57; Glennie et al., 2003). The Embla Field in the adjacent Norwegian sector (Marshall and Hewett, 2003; Ohm et al., 2012) utilises the same petroleum system.

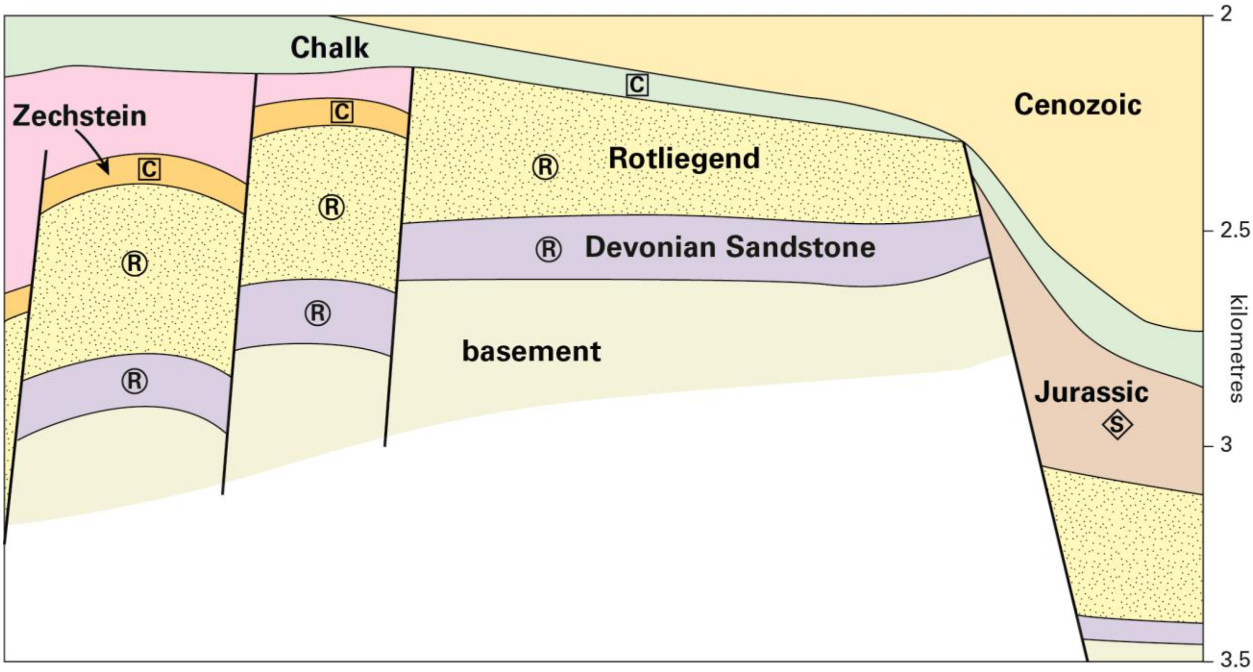


Figure 57 Summary of the Auk Field Block 30/16: Zechstein carbonate, Rotliegend and Devonian sandstone reservoirs in the footwall fault block adjacent to Jurassic mudstone source rocks. Simplified from Glennie et al. (2003) to illustrate the Jurassic–sourced, structural trap play of the Auk-Flora ridge area

As the remaining potential of the Auk-Flora ridge is at block/prospect level and there was little geochemistry, biostratigraphy and porosity-permeability data available, it was not studied in detail here. Instead a general account is given from the Palaeozoic perspective.

The Auk-Flora ridge forms the north-eastern boundary to the North Dogger and Quadrant 29 basins. In Quadrant 30, the Kyle Group rests unconformably on basement and reservoir intervals occur in the Buchan Formation and Rotliegend. A Zechstein or Chalk seal is present (Figure 57). Further south in Quadrant 31, uppermost the Carboniferous (Westphalian-Stephanian), Flora Sandstone and Grensen formations are proven by wells (see Kearsey et al., this study), with the former comprising the reservoir in the Flora Field (Martin et al., 2002). In Quadrant 39, lower Carboniferous Yoredale and Scremerston formations on the north-eastern side of the North Dogger Basin (Figure 28) unconformably underlie the uppermost Carboniferous sandstones.

Carboniferous or Devonian source rocks have not been interpreted on the Auk-Flora ridge in Quadrants 30 and 31. Though migration of gas from possible Devonian sources to the west has been hypothesised (e.g. CGG, 2011) no geochemical typing data has been found by this study to evidence this. Reservoir intervals are clearly present in upper Devonian sandstones (Auk, Argyll fields; see section 6 below) and uppermost Carboniferous sandstones (Flora field). Zechstein carbonates form a reservoir in Quadrant 30 (Taylor, 1998). A Zechstein evaporite seal is missing from parts of the Auk-Flora ridge (e.g. Figure 57) and higher horizons such as the lower Cretaceous marl and upper Cretaceous chalk form the top seal (Hayward et al., 2003). Trap styles are structural fault and dip closures.

The risks in the Palaeozoic petroleum system of the Auk-Flora ridge are at block/prospect level. Seismic mapping of the late Carboniferous to Jurassic reservoir intervals is complicated by volcanic rocks and unconformities (see Martin et al., 2002), a structural geometry that allows migration from Jurassic source rocks must be in place and a top seal must be identified where Zechstein evaporites are absent.

5.6 FORTH APPROACHES

5.6.1 Overview

The potential Carboniferous petroleum system of the Forth Approaches is delineated in a series of fault-controlled basins between the offshore extensions of the Southern Upland and Highland Boundary faults (Figure 58).

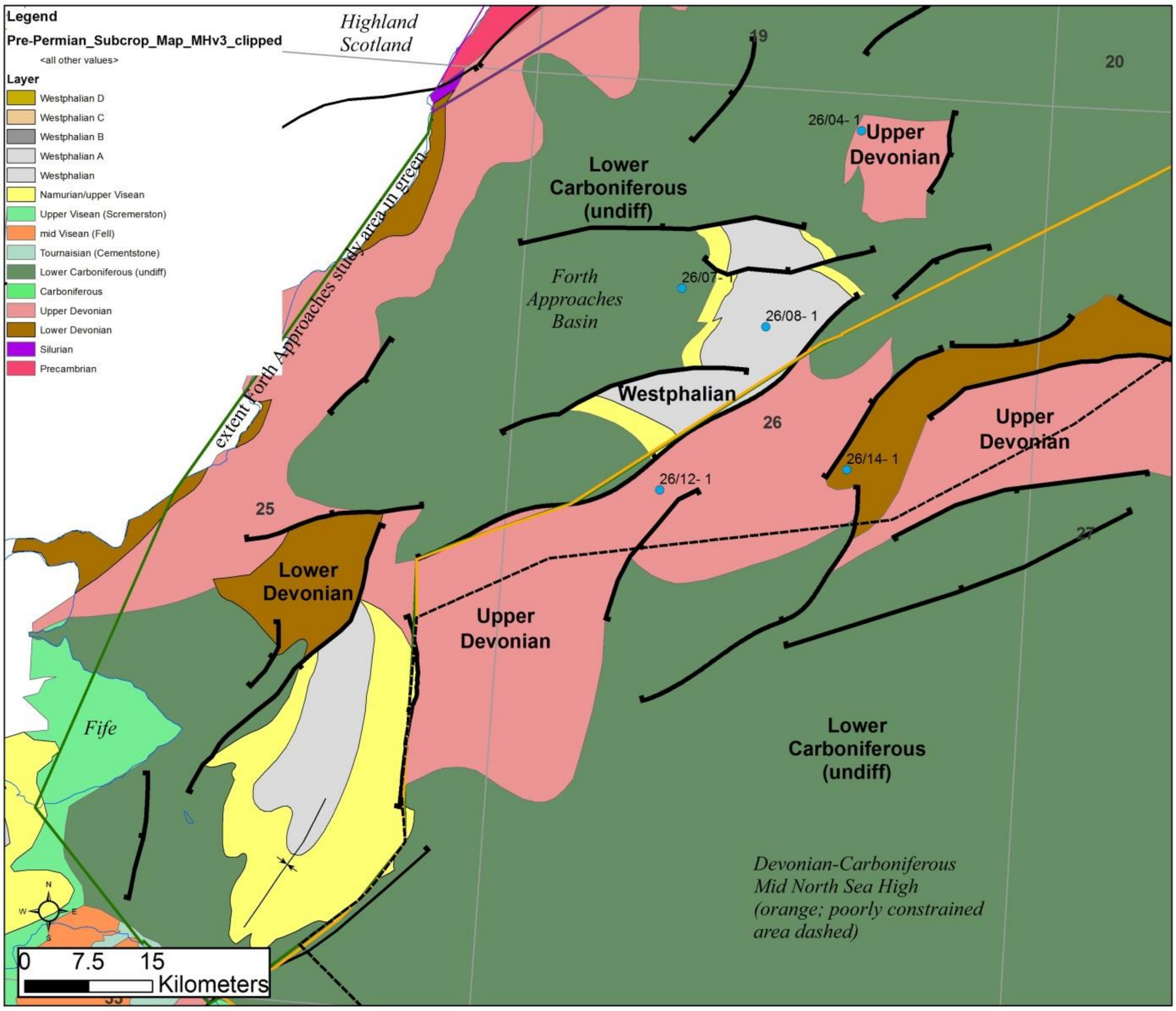


Figure 58 Pre-Permian subcrop map for the Forth Approaches and well distribution. The wells prove Firth Coal and Fell Sandstone formations within the lower Carboniferous (undifferentiated) unit but it was not possible to map these horizons seismically.

Two wells 26/07-1 and 26/08- 1 indicate a >1 km thick Carboniferous sequence with similarities to the Midland Valley of Scotland that lies 80 km to the south-west. In the two wells, the Firth Coal Formation contains numerous coals and is the time-equivalent of the Scremerston Formation. The underlying unit, previously named the Tayport Formation (Cameron, 1993b) comprises blocky sandstones and is similar to those seen in the age-equivalent Fell Sandstone Formation further south (a Fell Sandstone Formation assignment is used in this study or ‘Tayport Formation in 26/07- 1’ to distinguish this unit from the older Tayport Formation interpreted in Quadrant 37, Dutch Sector etc). Seismic mapping on top Cementstone Formation delineates a relatively small half-graben basin in Quadrant 26 reaching depths of over 4km (Figures 58, 59, Arsenikos et al., this study). Seismic data quality does not allow interpretation to continue to the north-east, where the gravity inversion surface indicates a sedimentary basin (Kimbell & Williamson, this study).

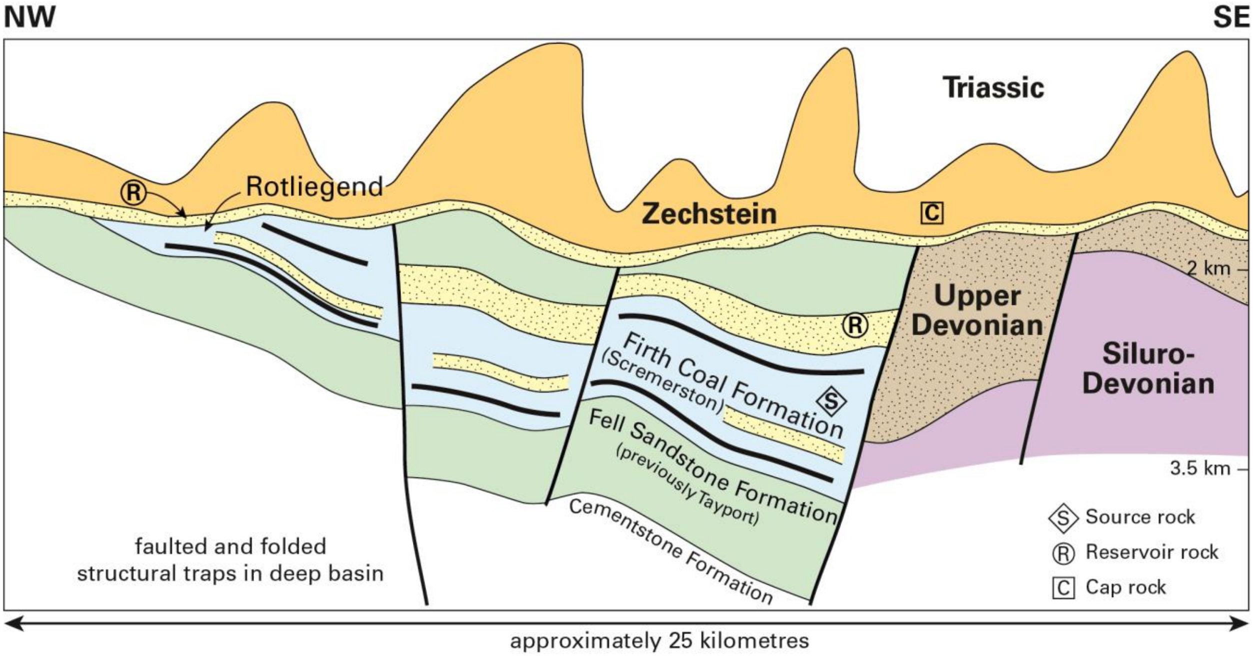


Figure 59 Summary cartoon of the Forth Approaches Carboniferous play system

The petroleum system in the Forth Approaches is envisaged to be largely a structurally controlled lower Carboniferous clastic play sourced from coals, mudstones and any thin oil-shales within the Visean Firth Coal/Scremerston Formation (Figure 59). Clastic reservoirs of mid–late Carboniferous or Rotliegend age and possible Zechstein carbonate reservoirs are capped by Zechstein evaporites (Figure 59).

5.6.2 Fields, shows, discoveries

Well 26/07-1 contained an oil show in the Hauptdolomit and well 26/08- 1 contained gas and oil shows in the Firth Coal Formation. Fluid inclusion studies in these and surrounding wells suggest migration of Carboniferous, non-marine sourced gas to the upper Devonian and Rotliegend intervals (Farris, 2012).

In the Midland Valley of Scotland, a working lower–mid Carboniferous play exists. Numerous oil and gas shows, and production from the Midlothian field/D'Arcy-Cousland anticline in the 1940-1960's, are sourced, reservoired and trapped within lower Carboniferous rocks (Hallett et al., 1985, Underhill et al. 2008, Monaghan 2014).

5.6.3 Source rocks

The largely gas-prone Firth Coal Formation (Scremerston equivalent) source rock quality varies from poor to excellent in 26/07- 1 and 26/08- 1 (Vane et al., this study; Figure 60). Coals form a significant component of the succession. Westphalian, Coal Measures age-equivalent strata are recorded in 26/08- 1 and though mudstone intervals are present, coals are lacking.

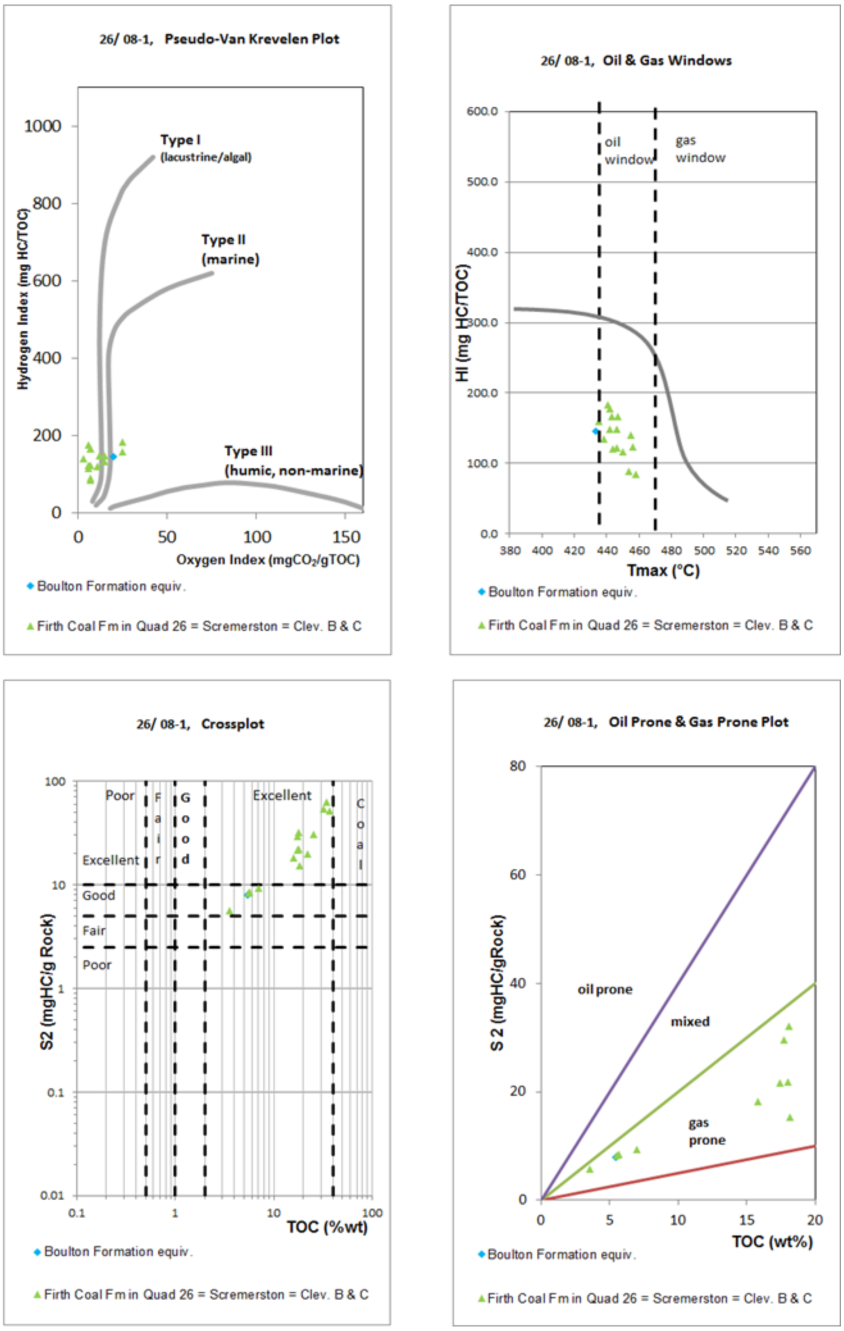


Figure 60 S1, Van Krevelen plot, HI vs T_{max} plot, S2 vs TOC plot, and oil prone and gas prone plot for well 26/08-1

The onshore, time equivalent (Visean) sequence in the Midland Valley of Scotland contains the organic-rich, oil-prone lacustrine West Lothian Oil-Shale Formation (Figure 61; Monaghan, 2014). The oil-shale strata in West Lothian pass laterally westwards into a mixed fluvial, deltaic and marine sequence in Fife and well L25/26- 1 (Firth of Forth 1), though thin oil shale beds are still present in Fife (Monaghan, 2014). Intercalated carbonaceous mudstones are present in an offshore BGS borehole 73/16 in south-eastern Quadrant 25 and oil shales are interpreted within the lower Carboniferous strata of well 20/10a- 3. An undrilled, restricted lacustrine basin of similar size to that in West Lothian could exist in the Forth Approaches area given the sparse well penetrations.

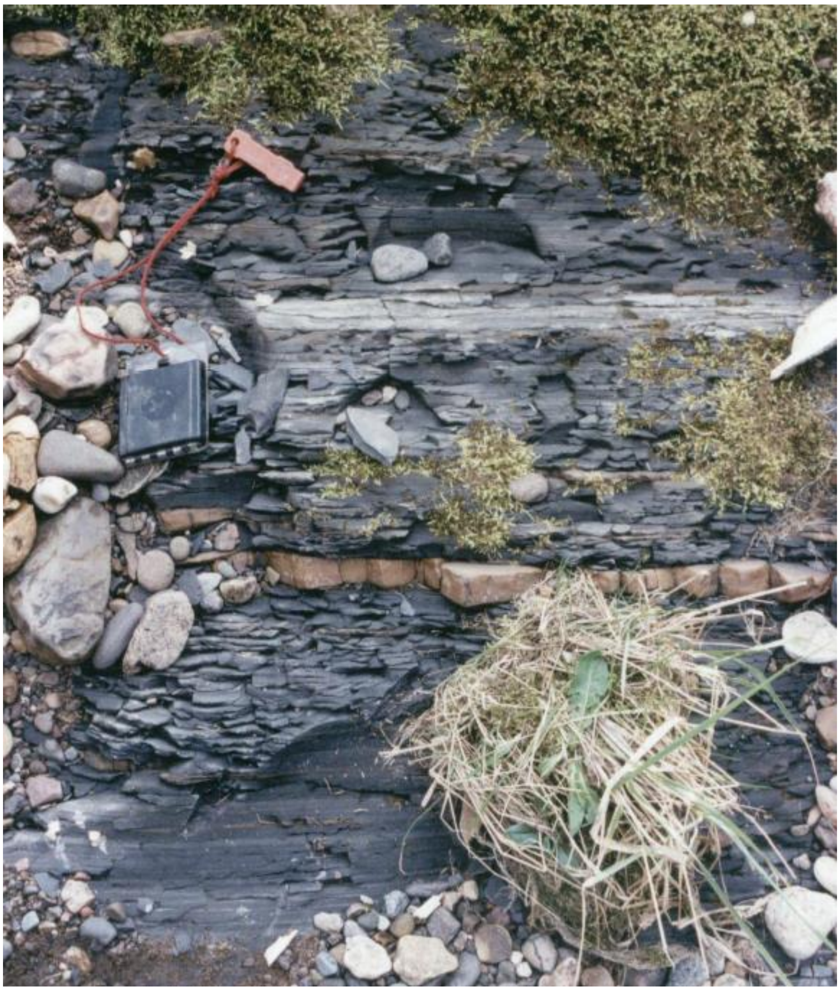


Figure 61 Laminated grey lacustrine mudstone facies of the West Lothian Oil-Shale Formation from Jones (2007). Note the thin silty sandstone bed (grey) above the compass and the brown ironstone bed below the compass. Linhouse Water, West Calder Wood.

Petrophysical calculation in the Firth Coal Formation of 26/07- 1 and 26/08- 1 gave an average TOC contents of shales between 1.6-3.0 wt% with 44–45 % of the unit containing shale with TOC> 1wt% (Gent, this study, coals excluded; Figure 63). Coal Measures strata in 26/08- 1 gave a calculated average TOC of 1.7% with 41% of the unit containing shale with TOC> 1wt% (Gent, this study, coals excluded). Coals form a significant part of the succession in the wells examined and form an important component of the source rock. However, coals were excluded from the petrophysical analysis as the method is not accurate for coals (see Gent, this study), resulting in an underestimate of source rock potential.

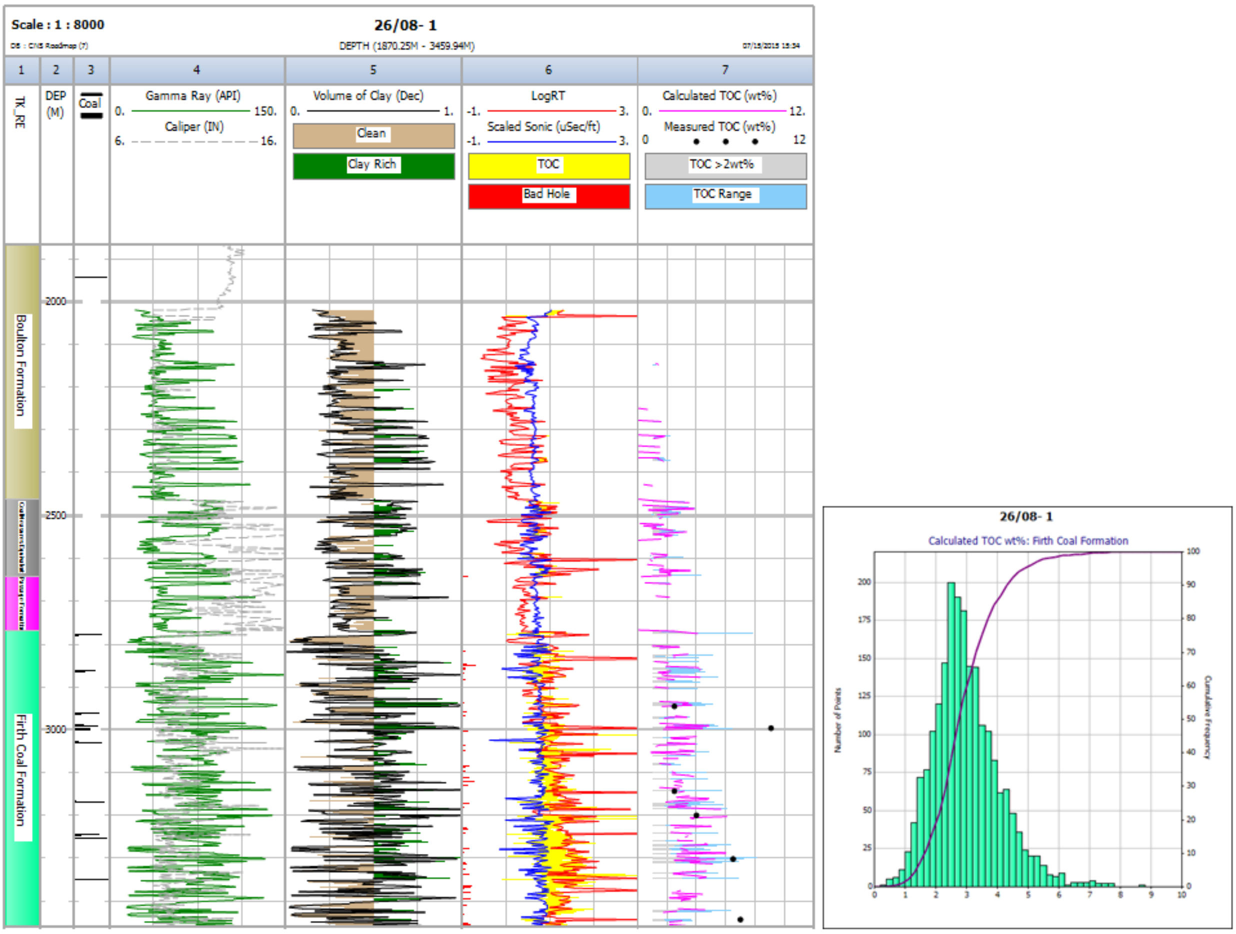


Figure 62 Petrophysical calculation plot for TOC content of shale in well 26/08- 1 and histogram of calculated TOC contents from Gent (this study). Note that coals are excluded from the petrophysical calculation but are shown in column 3 of the plot where they have been interpreted from wireline log curves.

5.6.4 Maturity, migration and charge

Previous basin modelling and fluid inclusion work has interpreted both a Late Carboniferous phase of migration and charge before traps and seals were in place (Glenister, 2001) and a Mesozoic-Cenozoic gas generative phase once traps and seals were in place (Granby & TGS Nopec, 2010).

Maturity data shows the Firth Coal (Scremerston equivalent) Formation reaches oil window maturity in the two wells drilled (Vane et al., this study). However as the sampled succession is largely gas prone, the basin modelling that indicates early oil maturity during Carboniferous burial and mid–late oil maturity during Mesozoic- Cenozoic deeper burial in 26/08- 1 is not likely to generate significant quantities of oil or gas (Vincent, this study, Figure 63).

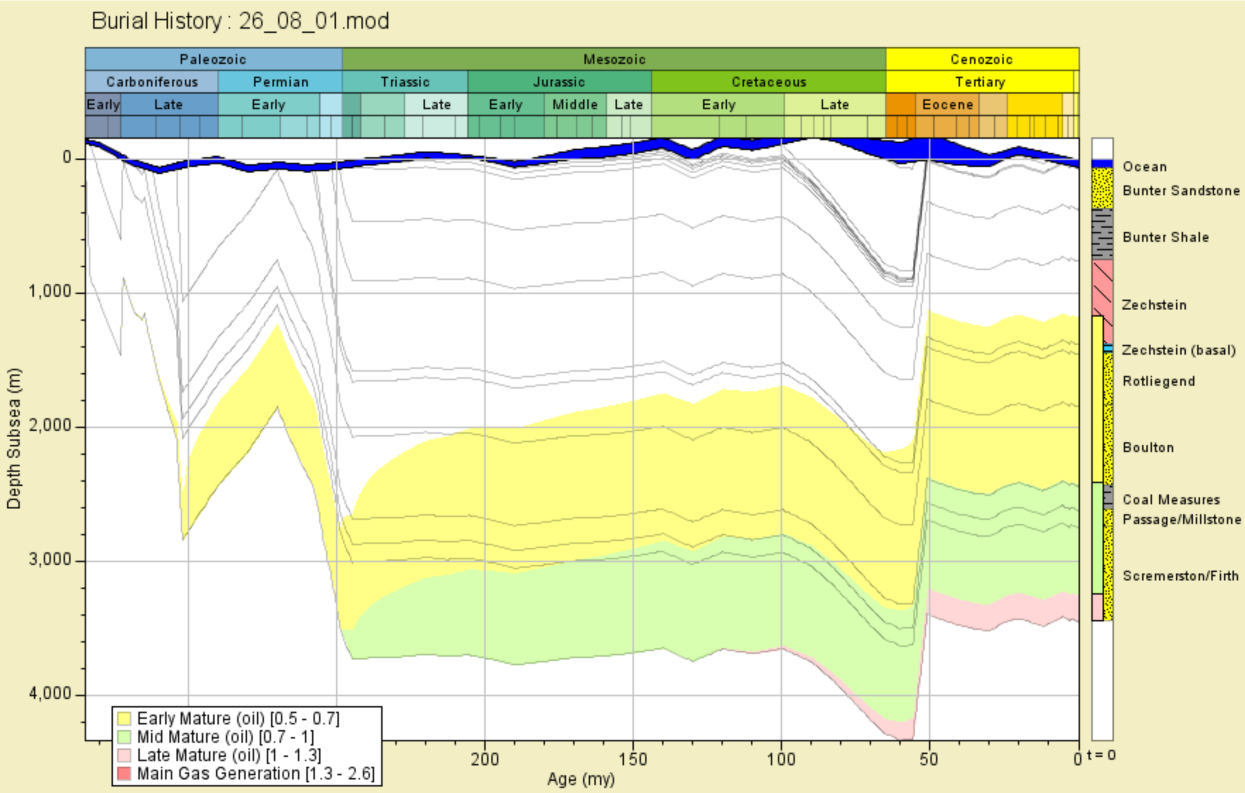


Figure 63 Burial history plot for 26/08- 1 from Vincent (this study) showing strata reaching the oil window in Carboniferous, Mesozoic and Cenozoic times

Relatively small amounts of additional burial compared to the studied well or a more oil-prone sequence, both of which could occur in the Forth Approaches basin, could significantly enhance the prospectivity of the lower Carboniferous petroleum system. Traps and seals would be in place for Cenozoic charge but not for earlier Carboniferous charge. Vincent (this study) estimated that a well drilled in the deepest part of the basin (over 700 m deeper than 26/08- 1) would be gas mature at Firth Coal Formation (Scremerston equivalent) source rock level. However the volume of thus unit reaching the maximum depths is small.

5.6.5 Reservoir rocks

The main reservoir target in this area is likely to be the Rotliegend, Auk Formation sandstones that are 150 m thick in 26/07- 1 with porosity of 5.7–24.2% and permeability of hundreds of millidarcies. Additional potential reservoirs are present throughout the heterolithic Carboniferous succession.

High porosity and permeability values of the Firth Coal (Scremerston) Formation core samples (see section 2.3 above) in 26/07- 1 were from cores taken at 5–15 m thick sand bodies. These intervals are mid Asbian age and are correlated to the Sandy Craig Formation onshore in Fife, see Figure 64.

Figure 64 Newbigging Quarry, Burntisland, Fife: thick, soft sandstone of fluvio-deltaic origin, Sandy Craig Formation. BGS Photo P265438

Petrophysical work has shown the Firth Coal (Scremerston) Formation to have calculated average porosity of 13% and NTG of 0.19 in 26/07-1 with average permeability estimated at 261 mD. Measured core values for porosity are an average of 18% with an average permeability of 295 mD. Values for the Fell Sandstone ('Tayport in 26/07- 1') Formation are an average porosity of 11% and NTG of 0.52, with an average permeability of 15mD (Hannis, this study).

5.6.6 Seal rocks

Though strongly affected by halokinesis, Zechstein evaporites are likely to form the main seal rock in the Forth Approaches area (Figure 59). Local intraformational mudstone seals within the Carboniferous are possible and must be effective onshore to trap the Midlothian Field in the faulted D'Arcy-Cousland anticline.

5.6.7 Traps

A variety of structural trapping styles are observed on seismic resulting from relatively complex folding and faulting (Figure 65, Arsenikos et al. this study). Improved quality seismic data is required to map the structures in 3D.

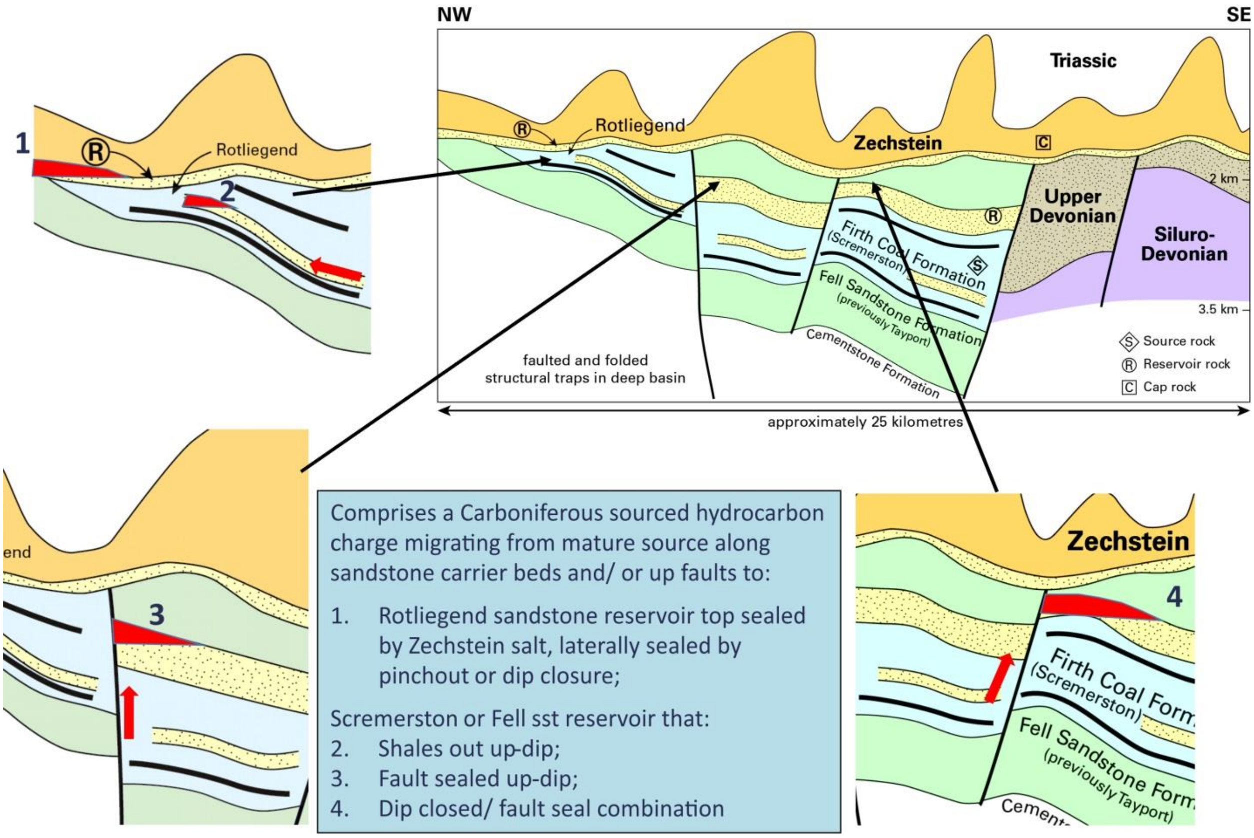


Figure 65 Examples of possible trapping styles in the Forth Approaches

5.6.8 Knowns and risks

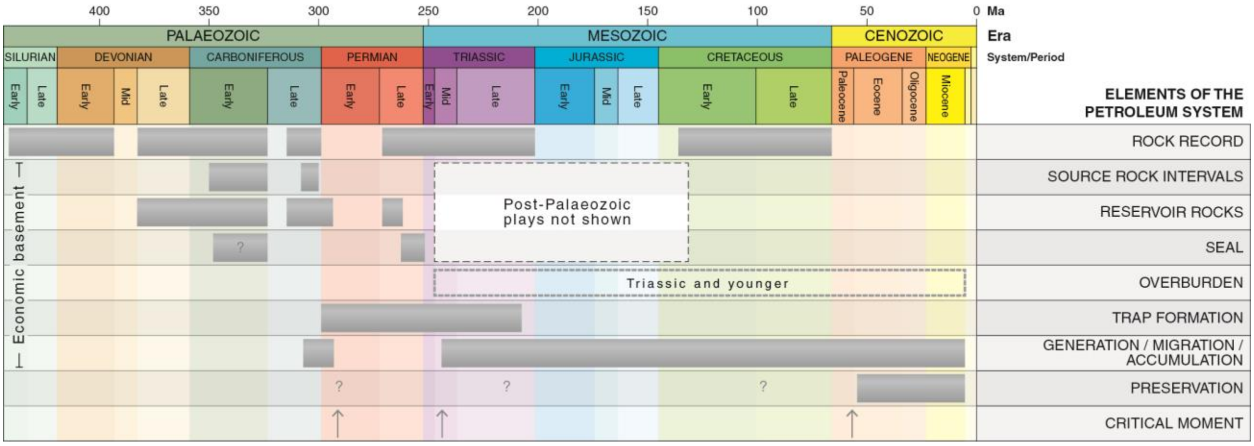


Figure 66 Critical elements summary for the Forth Approaches

In the Forth Approaches, all the elements of the petroleum system are in place within the Carboniferous and Permian, and there are multiple potential opportunities within a stacked system. Oil and gas shows offshore suggest source rock types are present and mature. Along strike onshore in the Midland Valley, a Carboniferous petroleum system has previously been exploited.

Critical to the prospectivity of the Forth Approaches is the volume of source rock, timing and level of maturation (Figure 63, 66). Any Carboniferous generation and charge would likely have occurred before traps were in place, unless intraformational Carboniferous seals are effective. Basin modelling shows oil window levels of maturity in 26/08- 1 at the level of largely gas prone source rocks (Vincent, this study). Gas mature intervals may be present in the deepest parts of the basin but the volume of gas mature strata at the Cenozoic critical moment is modelled as being limited. That is, the volume of gas-mature source is likely to be a critical factor. If extensive lacustrine oil-shales were proven offshore then an oil-prone play could be prospective based on current basin modelling.

Seismic data quality and spacing is a risk to mapping relatively complex structures and in defining possible Carboniferous basins to the north-east. Intra-Carboniferous reservoir quality is variable and difficult to predict.

6 Results: Devonian petroleum system

6.1 OVERVIEW

In Quadrants 25–44, the elements of the Devonian petroleum system are poorly defined by data.

The upper Devonian to lowermost Carboniferous sandstone-dominated, potential reservoir intervals of the Buchan, Tayport and parts of the Cementstone formations (see Figure 2) are mapped as regionally extensive (Figure 67) but are sampled by a small number of wells. This interval is of variable thickness in response to extension/transtension and is seismically mapped to reach over 4 km in the North Dogger Basin, 2 km on the northern margin of the Silverpit Basin, as opposed to 300m in 37/12- 1 on the Dogger Granite high.

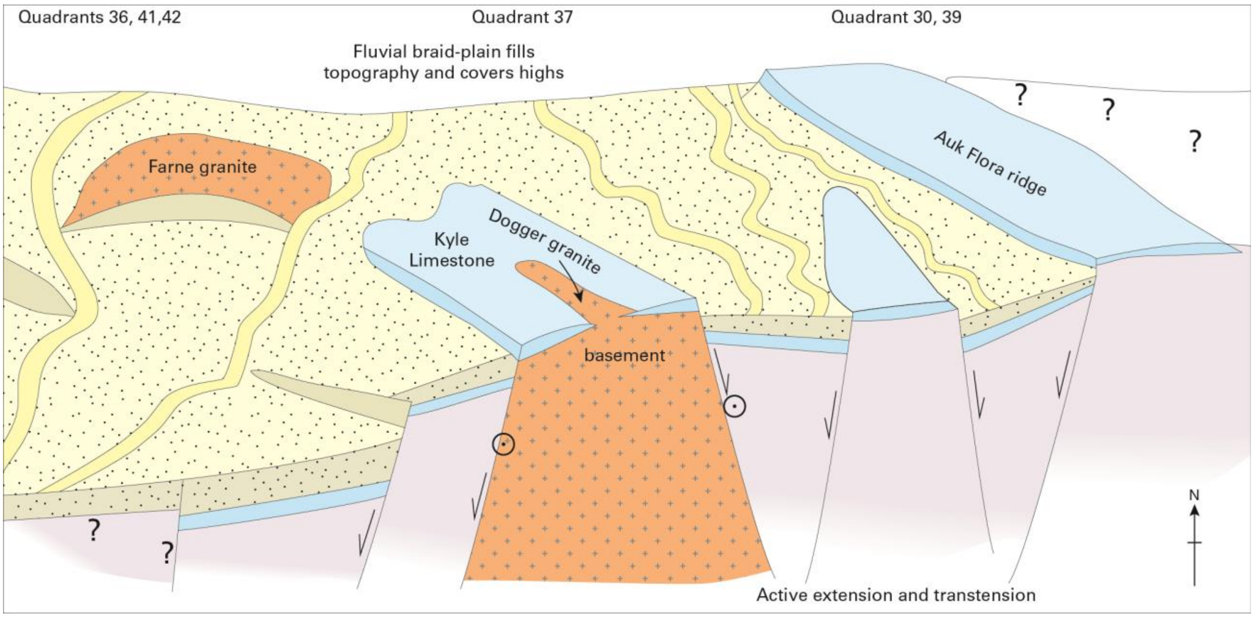


Figure 67 3D generalised cartoon of upper Devonian structure and depositional environment across the southern part of the study area (Quadrants 35–44). The topography on the cartoon is exaggerated and further infilling occurs such that upper Devonian deposits cover all of the highs.

The mid Devonian Kyle Group is of exploration interest due to analogues from Canada and Russia where a self-contained Devonian petroleum system of carbonate reservoir, source rock and seal are in close proximity. Whilst proven only in a small number of wells drilled on regional highs, the Kyle Group forms a regional seismic marker and has been picked extensively (Figure 68). The mid Devonian is absent across a major unconformity onshore northern England and central Scotland (e.g. Hutton's unconformity at Siccar Point). It is unclear from the seismic interpretation whether the Kyle Group extent is the result of truncation by the mid Devonian, Acadian unconformity observed onshore, or whether there is a lateral facies change from the seismically-reflective limestones. The 2015 Government-funded seismic data will hopefully provide evidence of truncation by erosion or a lateral facies change into a marginal sequence which may contain the untested petroleum play. An overview of the possible play is given in Figure 69.

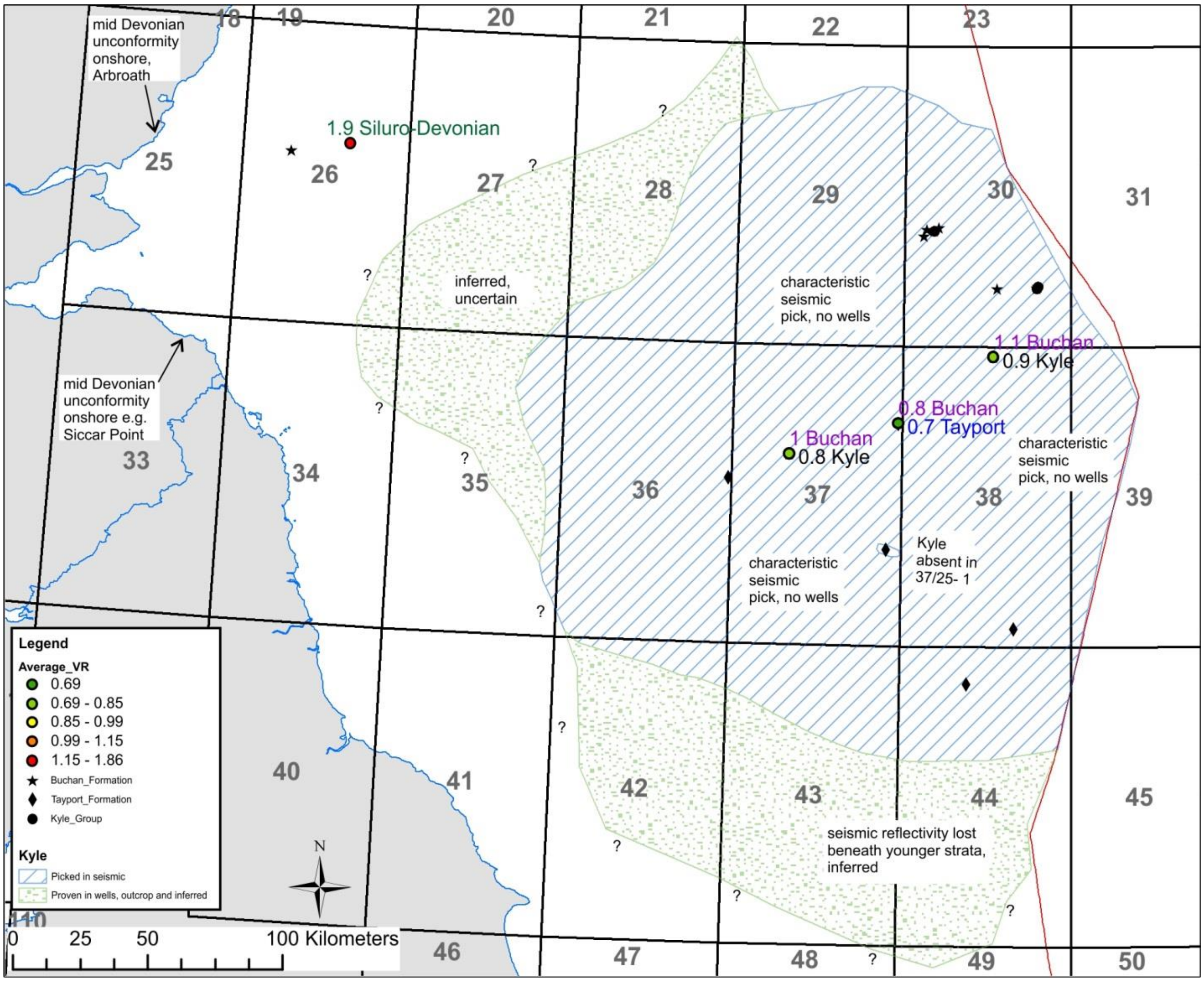


Figure 68 Extent of mid Devonian Kyle Group, together with vitrinite reflectance average maturity values (measured and calculated) from wells for a variety of Siluro-Devonian, Devonian and lowermost Carboniferous units, plus symbols showing wells proving those units where maturity data is unavailable.

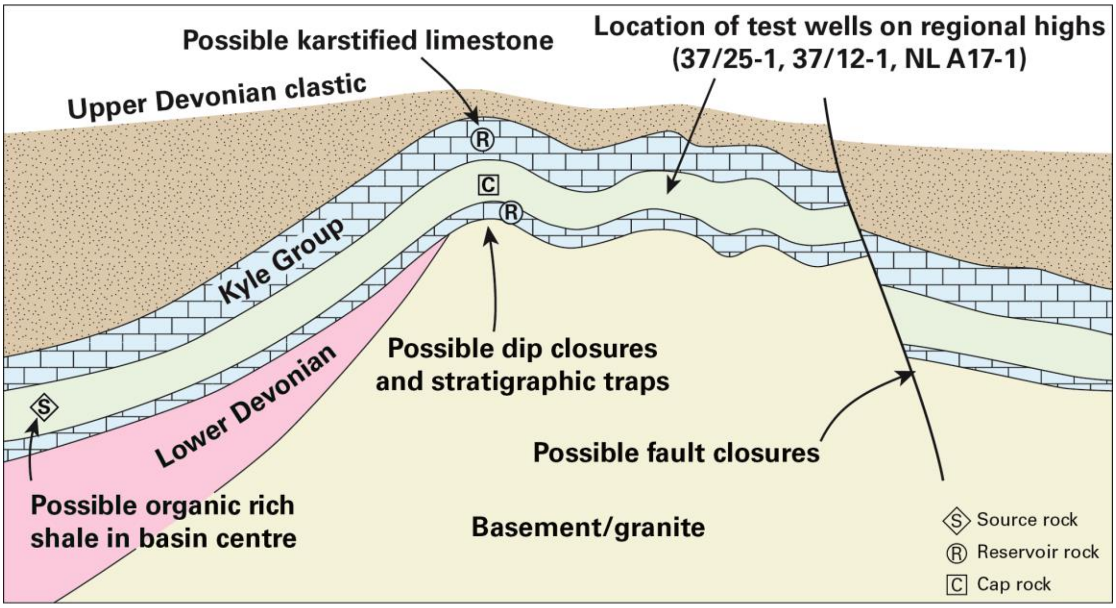


Figure 69 Cartoon of the possible mid Devonian Kyle Group play. Karstified reefal carbonates are envisaged as the reservoir interval on regional highs. Basinal mudstones would form the source rock and intercalated mudstones would form seals. Note that 37/25-1 tested the play, but the Kyle Group was absent at that location.

In parts of Europe e.g. the Ardennes, lower Devonian extensional basins were filled with shale (Belka et al. 2010). Wells penetrating lower Devonian strata in Quadrants 26 and 27 encountered variably altered, sheared and veined mudstone and sandstone and wells 37/25- 1, 30/16- 5 farther south encountered 'basement' beneath the Kyle Group. Thus there is no data to constrain any putative basinal lower Devonian mudstone facies.

6.2 FIELDS, SHOWS, DISCOVERIES

To the west and north of the Mid North Sea High, upper Devonian sandstones form the reservoir in the Jurassic-sourced Auk, Argyll (oil), Embla (Norwegian sector), Buchan (oil), Stirling (oil) fields (Marshall and Hewett, 2003). The reservoir rocks are low-permeability fluvial sandstones with production enhanced by a network of open fractures.

No hydrocarbons are currently produced from the Devonian of the Southern Permian Basin area, though Devonian successions are locally very thick and contain carbonate and clastic rocks of good reservoir quality (Belka et al., 2010).

Well 37/25- 1 tested the Devonian Kyle Group play on the 'Corbenic' prospect of the Dogger granite high and was prognosed to encounter reefal carbonates (ExxonMobil, 2010). The well penetrated Buchan Formation to Caledonian basement and was dry. Post-well seismic examination interpreted Kyle Group close to the well location (ExxonMobil, 2010). Other wells drilled into the Devonian on regional anticlinal or fault block highs have also been dry (37/10- 1, 37/12 -1, 38/03- 1).

6.3 SOURCE ROCKS

Given the >3 km depths of seismic grids for much of the Top Kyle Group over much of the study area (Figure 29) and the resultant likely maturity levels, an assessment was made of source rock potential. However, cuttings and core material were limited to five wells drilled on regional highs. Thus the dataset may not be representative and organic rich mudstones may exist in more basinal locations, as is the case in the Orcadian Basin (Marshall and Hewett, 2003) and in south-west England (Edmonds et al., 1975).

Source rock quality of both the upper and mid Devonian succession was poor (Vane et al., this study, Figure 8 above, Figure 70). TOC contents were generally <1 wt% and S2 values generally fell within the poor category. Maturity values are somewhat scattered but on average are approximately oil window (Figures 68, 70). Previous work has interpreted thin coals within the Buchan Formation of 38/03- 1 and some studies have hypothesized that these coals could form a mature gas source (CGG, 2011). The evidence for coals or possible contamination within 38/03-1 has been debated, see Schroot et al. (2006, page 51) for a detailed description. It has not proven possible to further the debate during this study, though it is noted there is an inconsistency between the wireline log responses, which could be taken as indicative of coal, and numerous geochemical analysis data where TOC < 1wt% (Gent, this study, well plot).

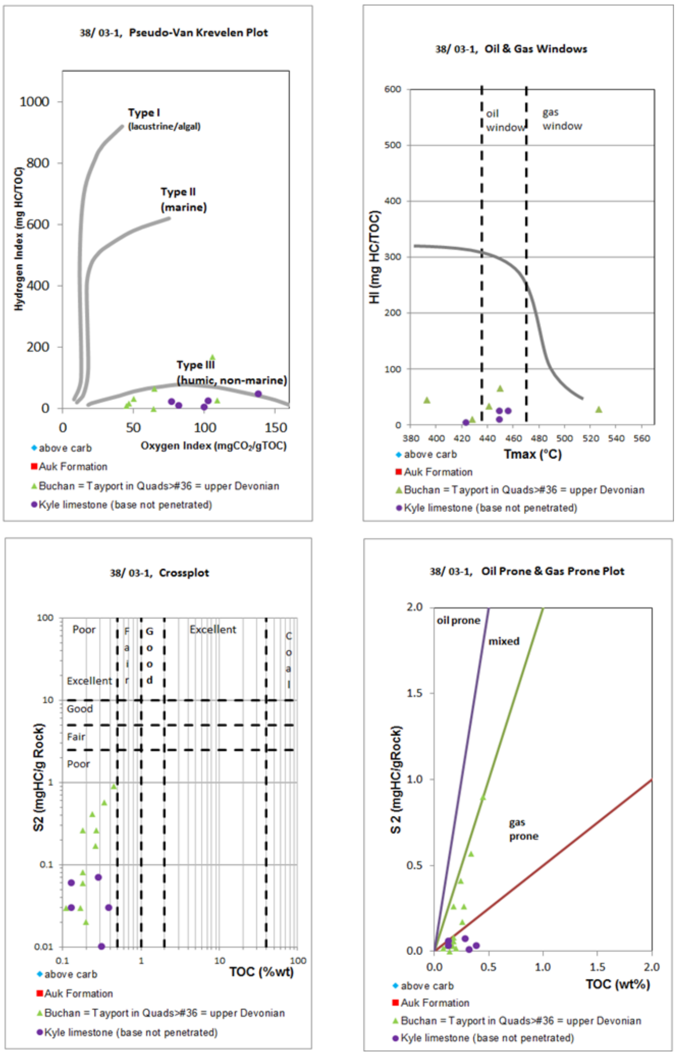


Figure 70 Selection of plots to illustrate source rock quality and maturity in the upper Devonian (Buchan Formation) and Kyle Group of well 38/03- 1.

Petrophysical analysis for the Devonian strata mirrored the findings of the organic geochemistry work, that the TOC contents of the rocks are low. Analysis of the lower Devonian in 26/14- 1 gave an average TOC of 0.7% with only 7% of the unit having TOC > 1wt%, though it was noted that this is likely an overestimate given the constraining data points (Gent, this study). In 37/12- 1 and 38/03- 1 the Buchan Formation gave an average TOC of 1 – 1.2 wt% and the Kyle Group 0.6–1.6 wt %, but again this was thought to be an overestimate when compared to the constraining data points (Gent, this study, see log plot).

In summary, the limited number of wells penetrating the mid and upper Devonian interval on regional highs prove a poor quality source rock. However the character of the strata is unknown in slope or basinal settings that should have greater potential for deposition of organic-rich shale.

6.4 MATURITY, MIGRATION AND CHARGE

Oil window maturity is indicated in wells penetrating the mid–upper Devonian intervals (Figure 68) on regional highs in Quadrants 37 and 38. Given the poor quality of the source rock, no basin modelling was performed in this study. However the Buchan and Kyle Groups are buried significantly deeper in adjacent basins where they may have reached gas to overmature levels.

6.5 RESERVOIR ROCKS

In the Buchan Field, the Devonian-Early Carboniferous reservoir is described as red, arkosic to subarkosic sandstone with siltstone, mudstone and calcrete pebble conglomerate (Edwards, 1991). Average porosity is typically 5-7% with permeability 0.2-20 mD, however fractures increase the average permeability to 38 mD (Bruce and Stemmerik, 2003). In the Argyll Field the upper Devonian reservoir of sandstone, conglomerate and mudstone has poor to fair reservoir quality due to quartz and dolomite cementation (Marshall and Hewett, 2003). Reservoir quality improves in younger parts and fracturing is significant close to faults (Marshall and Hewett, 2003). Figure 71 shows an upper Devonian conglomerate and sandstone outcrop onshore Scotland.

Figure 71 Conglomerate and sandstone, Seaton Cliffs Arbroath, upper Devonian Burnside Sandstone Formation, Stratheden Group - age-equivalent of the Buchan Formation offshore. BGS Photo P638723 BGS©NERC. All Rights Reserved 2016.

In the wells examined for this study, core measurements from the Buchan Formation and Kyle Group gives porosities less than 6% in 37/12- 1 and permeabilities 0.1mD or less. Petrophysical calculation gives average porosity of the Buchan Formation from 6–12 %, with a maximum of 29% and a NTG of 0.73 in 37/10- 1.

6.6 SEAL ROCKS

Upper Devonian potential reservoirs occur over a wide area and could be sealed by overlying Carboniferous strata or where close to base Permian subcrop, Zechstein evaporites.

In the potential self-contained mid Devonian Kyle Group play, mudstones within the Kyle Group would be considered as seal rocks. The relinquishment report for well 37/25- 1 notes that no top seal was present (ExxonMobil, 2010).

6.7 TRAPS

Notwithstanding the uncertainties in source, reservoir and seal rocks described above, the structures mapped on seismic at regional scale at depth, and closer to the base Permian unconformity, provide various potential faulted and folded structural traps. The potential mid Devonian play could utilise stratigraphic trapping (facies variations from reefal carbonates to slope carbonate/mudstones) as well as the location on regional structural highs (Figure 69).

6.8 KNOWNS AND RISKS

The upper Devonian sandstones and conglomerates form reservoir intervals in several Jurassic-sourced fault-bounded fields (Auk, Argyll/Ardmore). The same reservoir interval, remote from the Jurassic source, has been penetrated by a small number of dry wells on regional highs in Quadrants 37 and 38.

The possible mid Devonian, Kyle Group play is high risk in that the current limited well dataset has not located a reefal, karstified carbonate reservoir or organic-rich mudstone source/seal as could be predicted from analogues. Where data is available, the Kyle Group has low porosity and permeability and is of poor source rock quality. However, so little data is available that it would not be wise to make regional generalisations.

7 Conclusions: knowns and risks for future exploration

7.1 OVERVIEW OF KNOWNS AND RISKS

The descriptions above have highlighted the variation within Devonian, Carboniferous and Permian petroleum systems of the Mid North Sea High and surrounding areas. A qualitative 'traffic light' summary Table 3 is given below in an attempt to provide a high level summary of the knowns and risks in each age and location of play *at regional scale.* These summaries are highly generalised and incorporate many variations that require to be further investigated by local studies. For example the southern North Sea Westphalian play components are all coloured green since there is an extensive working petroleum province, however locally there are likely to be risks with reservoir, trap etc. The summaries are also highly dependent on the amount and quality of data available. Boxes shaded in lighter colours indicate lack of data and that the assigned colour is low confidence.

Petroleum system	**1.Permian**	**2 Southern North Sea Westphalian**	**3.Southern MNSH margin lower–mid Carboniferous clastic play**	**4.Southern MNSH margin lower–mid Carboniferous basinal play**	**5.Lower–mid Carboniferous North Dogger/Quadrant 29**	**6.MNSH lower–mid Carboniferous clastic play**	**7.Forth Approaches Carboniferous**	**8.Auk-Flora Ridge Devono-Carboniferous**	**9.Upper Devonian-lower Carboniferous reservoir**	**10. Mid Devonian play Kyle Group**
Source	Minor sources within Zechstein Sourced from Palaeozoic for the most part, or Jurassic	Proven – Westphalian coals	Mainly gas prone Scremerston, Yoredale, Millstone Grit source rocks including coals, variable quality but including good-excellent	Geochem data indicates good gas prone source rocks though some poor ?depleted	Limited data indicates potential in Scremerston/ Yoredale source Lacking data for Q29	Generally source rock not known. Some source potential proven in Q36	Limited data indicates good source rock, but spatial extent may be limited	Existing play sources Jurassic. Lack of data to define Devono-Carboniferous source	No underlying source proven. upper Devonian in 38/03-1 inconclusive 'coals'	Poor source rock quality indicated – No wells in basin centre which could have been anoxic
Reservoir	Proven Rotliegend reservoir, though absent/thin/variable quality over parts of Quadrants 25–44	Proven – Westphalian reservoirs e.g. Ketch	Reservoir quality and geometry is variable – can be good e.g. Breagh	Reservoir quality and geometry is variable, poorly tested. ?Tight gas	Well data very limited but where present some reservoir intervals indicated	Little data, though sandstone-dominated rocks may be extensive	Possible intra Carboniferous Thick Rotliegend present	Proven reservoirs in Auk, Flora	Proven reservoir in Q30 fields but variable quality, enhanced permeability dependent on local fracturing.	No data/not proven
Seal	Proven: Zechstein evaporites, Silverpit Fm in south. Locally Zechstein may be faulted, thin or carbonate rich and higher risk.	Proven Zechstein seal. Some intraformational Carboniferous seals.	Fault seal and intra-Carboniferous seals may work locally Zechstein seal	Intra-Carboniferous seals may work locally in mudstone-dominated succession Zechstein seal	Not known in Carboniferous. Lack of data, intraformational seals may exist Zechstein seal. Risk in south-east from thin Zechstein?	Not known in Carboniferous. Lack of data, intraformational seals may exist Zechstein seal. Risk where Zechstein thin or carbonate dominated	Local intra-Carboniferous possible, present onshore Zechstein seal	Proven in fields – post Palaeozoic (e.g. Chalk) where Zechstein evaporites are absent	Sandstone dominated Zechstein seal required	Overlain by upper Devonian/lower Carboniferous sandstone. Intraformational mid Devonian mudstone possible but unknown
Traps	Proven structural, dip, unconformity traps at Base Permian Unconformity	Proven, dominantly faulted and dip closures	Possible structural, dip, unconformity and stratigraphic traps require local evaluation	Possible structural, dip, unconformity and stratigraphic traps require local evaluation	Possible, structural, dip, unconformity and pinch out traps, require local evaluation	Various structural traps possible but largely unknown	Various structural traps appear possible , require local evaluation	Various structural traps but special juxtaposition required to source from Jurassic	Structural traps possible but poorly defined on seismic	Various major anticlines and horst blocks at regional scale
Maturity, migration	Dependent on location, from underlying Carboniferous across much of area or faulted Jurassic in Q30/31	Proven by numerous gas fields	Proven in Breagh, though variable across the area. Immature for gas in north	Source rocks proven, mature. Some may be depleted at current day and have generated oil/gas	Data lacking from basin centres. Modelling of low confidence 'scenario wells' indicates oil but not gas maturity	Unknown, likely immature for gas across much of area so reliant on long-range migration	Immature for gas in wells, timing of migration may be early, small volume in deep basin gas mature	Proven system from Jurassic. Not proven for Devono-Carboniferous	Long range/ migration route required for system to work	Devonian source rocks appear oil mature on highs. Lack of data

Table 3 Qualitative indication of knowns and risks for conventional petroleum exploration plays using a traffic light scheme at regional scale in Palaeozoic petroleum systems of the CNS/MNSH. At block/prospect level risks are much more complex and dependent on local geology. Lighter colours indicate lack of data and lower confidence. The spatial and temporal extent of the numbered columns are indicated in Figure 72 below.

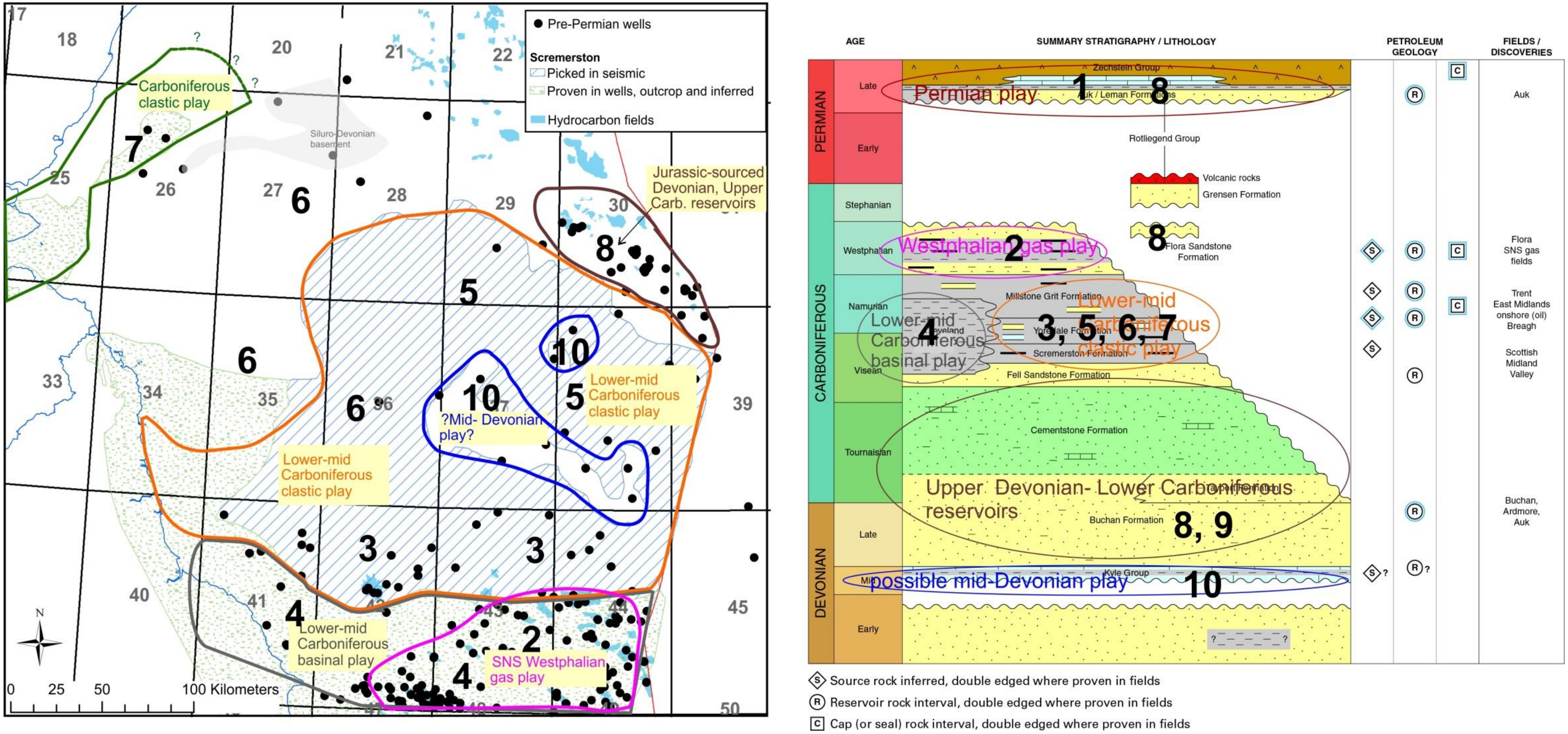


Figure 72 Indication of the spatial and temporal extent of petroleum systems described in the columns in Table 3 above. Note that where numbers are missing from the map the play type covers the majority of the area.

Given the complexity in the stacked Palaeozoic petroleum systems, the regional scale of this study and the lack of constraining data, it was considered more useful to describe the knowns and risks of the petroleum systems than to undertake a more detailed play fairway or common risk segment mapping. However the key elements can usefully be summarised in map view (Figure 73).

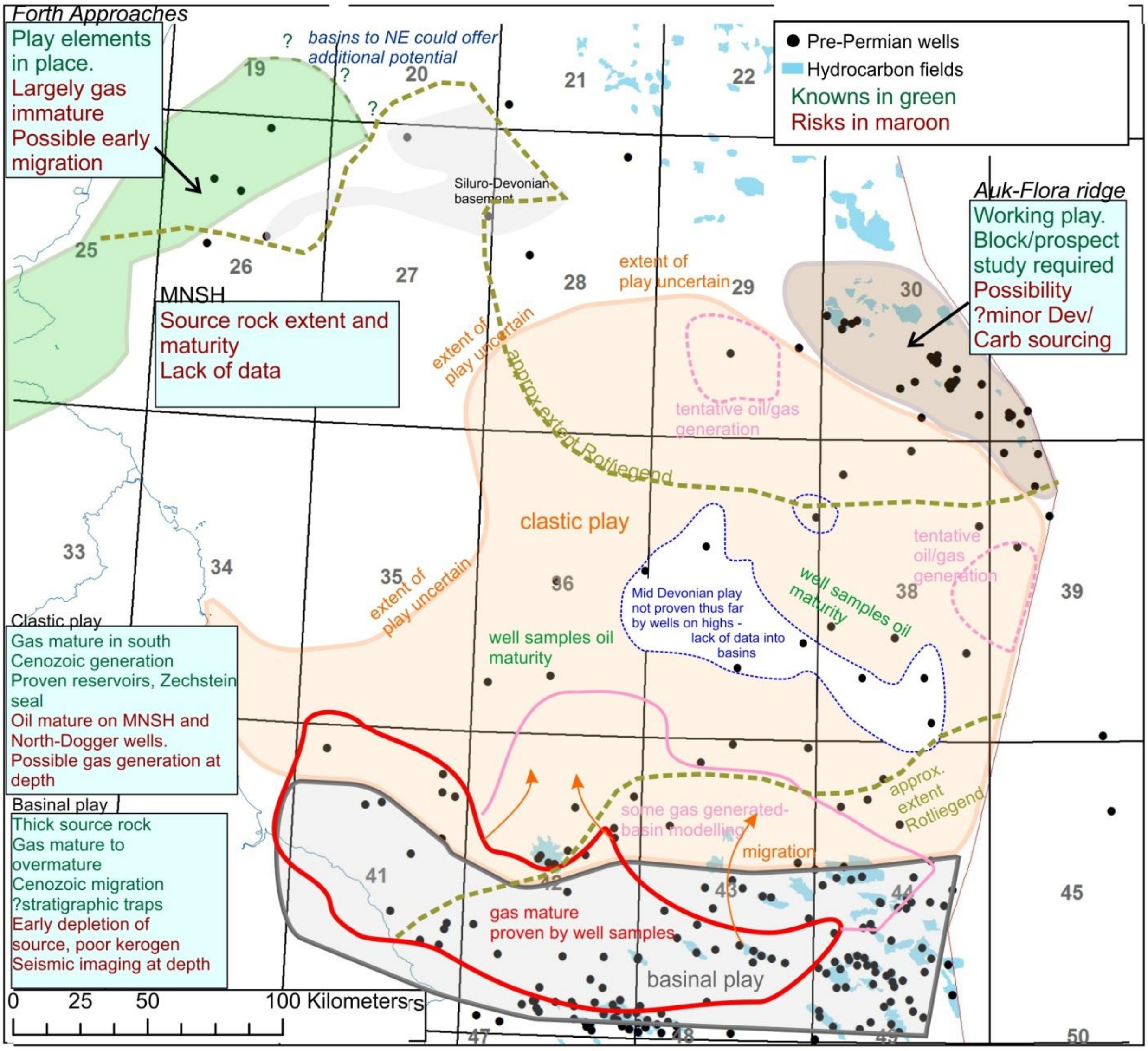


Figure 73 Summary map of knowns (green) and unknowns/risks (maroon) for the Palaeozoic petroleum systems considered.

Over southern Quadrants 26 to northern Quadrants 44 it is clear that the majority of wells are drilled on faulted/folded regional highs. However, mudstone source rock quality is likely to be best in basin centres, maturity is likely to be higher, and fluvial, deltaic and turbiditic channel sandstones are likely to have been focussed into lows. For this reason, detailed evaluation at prospect level of basin and slope/margin settings as well as of stratigraphic traps could be worthwhile. The Cygnus Field is a recent example that consideration of plays off the main structural high may be beneficial.

To summarise even further, Figure 74 is intended to give a generalised indication of lower–mid Carboniferous petroleum systems/locations with the most potential based on the currently available dataset.

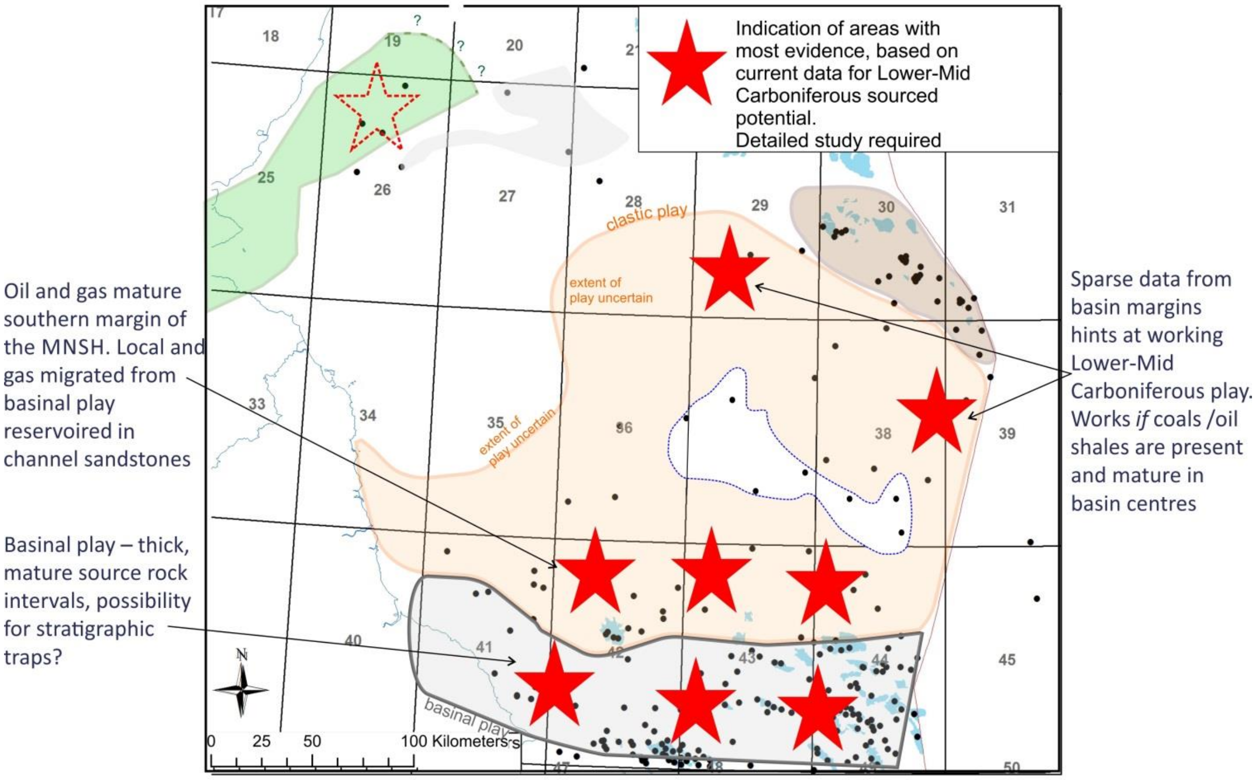


Figure 74 Indicative spatial summary of areas with the most evidence based on current data for lower–mid Carboniferous sourced potential petroleum systems.

In conclusion, the Palaeozoic project provides the data and interpretations to elucidate evidence for a working lower–mid Carboniferous petroleum system in Quadrants 25-44. The stacked, heterolithic plays reach several kilometres in thickness.

Key lower–mid Carboniferous (Visean–Namurian) source rock intervals are (Figure 75):

- Scremerston Fm/Firth Coal Formation
- Yoredale Formation
- Millstone Grit Formation
- basinal Cleveland Group

Key Devonian–Carboniferous reservoir intervals are (Figure 75):

- upper Devonian, Buchan Formation
- Fell Sandstone Formation
- Scremerston Formation
- Yoredale Formation
- Millstone Grit Formation

The current dataset provides evidence for intraformational Carboniferous seals onshore and in the Southern North Sea. Seismic mapping and detailed study of potential intraformational seals was out with the the scope of this study. However the main trapping style is structural at base Permian unconformity, sealed by Zechstein evaporites.

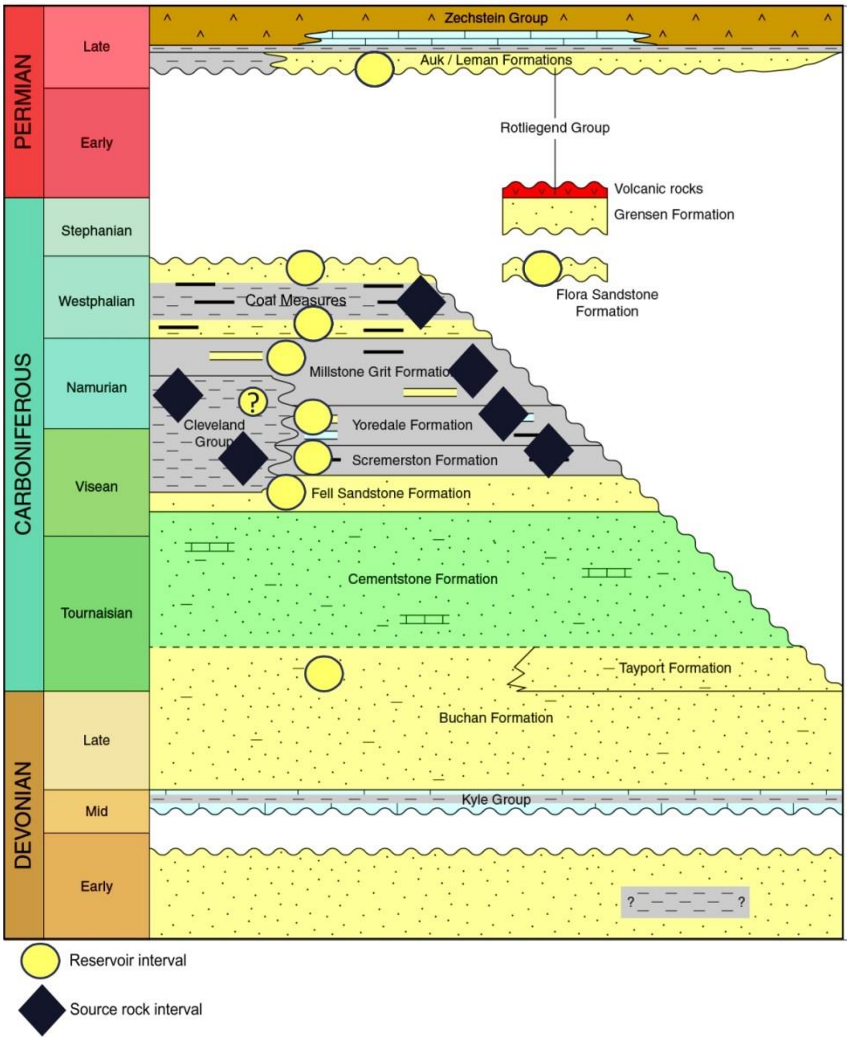


Figure 75 Summary of key source rock intervals (black diamonds) and reservoir intervals (yellow circles) identified in this study. Note the stacked and intercalated nature of source and reservoir intervals. Petroleum systems (plays) are shown on Figure 2.

At regional scale, the distribution of a mature source rock is the key controlling factor in the Palaeozoic petroleum system. A variety of dominantly gas-prone source rocks (coals, marine and lacustrine shales) are proven and a gas mature generative area has been delineated on the southern side of the Mid North Sea High in Visean and Namurian sequences. Over large parts of the study area, Visean and Namurian strata are within the oil window and the generative potential of thin oil-prone intervals merits more detailed study.

Reservoir and cap rock quality, as well as structural geometries and timing of maturity/ migration vary at block/prospect level. There is clearly potential for the positive play elements that have worked successfully in the Breagh field to be present at other locations. In addition, new stratigraphic and structural play types requiring intraformational Carboniferous sealing appear worthy of exploration given knowledge of producing fields onshore UK and in the SNS gas basin. Tight gas in the mid-late Carboniferous basinal play is another potential opportunity given the maturity and organic richness of this thick succession.

8 Future work

Numerous complementary or detailed studies have been out with the time and resource of the Palaeozoic project. Where data allows, studies such as offshore sequence stratigraphy, compilation and interpretation of petrographical data for example for reservoir quality and diagenesis studies etc., as well as new analyses e.g. apatite fission track for burial history or additional Rock-Eval, vitrinite reflectance and biomarker analyses, would add greatly to more detailed interpretations.

Two geochemical, source typing datasets that do not exist or were not located during the study would be of great benefit to answer the questions 1) where has the gas in Breagh, Crosgan come from – local Visean or Namurian sources or more distant Westphalian sources? 2) what is the source of the gas chimneys seen in Quadrant 29 by Hay et al. (2005)?

There are also some fundamental themes that it would be beneficial to consider for future work:

- Regional study of the Rotliegend and Zechstein – critical reservoir and seal intervals for the Carboniferous plays
- Tight gas, intraformational seals, stratigraphic traps within the lower–mid Carboniferous basinal play. Intraformational seals in the clastic play.
- Linked to detailed work on depositional environments and burial history – channel sandstones and organic rich mudstones in basin centres, off the highs currently drilled.
- Further work with the adjoining Dutch, Norwegian etc. sectors
- Further work linking onshore and nearshore, perhaps with a focus on unconventional hydrocarbons and tight gas
- Integration of the 2015 Government-funded seismic dataset
- The generative capacity of relatively thin oil prone intervals within the Carboniferous
- Geochemistry/source rock typing of shallow gas in Quadrant 29 and possibly a seep survey and analysis in areas with little or no well data – to allow firmer conclusions about the extent and potential of Palaeozoic sourced hydrocarbons in that area. Similarly, detailed source typing of other shows and discoveries.

References

Project reports, this study

ARSENIKOS, S., QUINN, M.F., PHARAOH, T., SANKEY, M AND MONAGHAN, A. 2015. Seismic interpretation and generation of key depth structure surfaces within the Devonian and Carboniferous of the Central North Sea, Quadrants 25 – 44 area *British Geological Survey Commissioned Report*, CR/15/118. 66pp.

GENT, C M A. 2015. Total organic carbon calculation using geophysical logs for 31 wells across the Palaeozoic of the Central North Sea . *British Geological Survey Commissioned Report*, CR/15/121. 74pp

HANNIS, S. 2015. Reservoir evaluation of 12 wells in the Devonian ‐ Carboniferous of the Central North Sea: Petrophysical interpretations of clay volume, porosity and permeability estimations. *British Geological Survey Commissioned Report*, CR/15/120. 55pp

KEARSEY, T, ELLEN, R, MILLWARD, D. AND MONAGHAN, A.A. 2015. Devonian and Carboniferous stratigraphical correlation and interpretation in the Central North Sea, Quadrants 25 – 44. *British Geological Survey Commissioned Report*, CR/15/117. 80pp

KIMBELL, G S, WILLIAMSON, J P. 2015. A gravity interpretation of the Central North Sea. *British Geological Survey Commissioned Report*, CR/15/119. 75pp

LESLIE AG, MILLWARD D, PHARAOH T, MONAGHAN AA, ARSENIKOS S, QUINN M, 2015. Tectonic synthesis and contextual setting for the Central North Sea and adjacent onshore areas, 21CXRM Palaeozoic Project *British Geological Survey Commissioned Report*, CR/15/125. 30pp

MONAGHAN A A AND THE PROJECT TEAM. 2016. Overview of the 21CXRM Palaeozoic Project – a regional petroleum systems analysis of the offshore Carboniferous and Devonian of the UKCS. British Geological Survey Commissioned Report, CR/16/047. 21pp

VANE, C H, UGUNA, C, AND KIM, A W.. JOHNSON, K, MONAGHAN A**.** 2015. Organic Geochemistry of Palaeozoic Source Rocks, Central North Sea (CNS). *British Geological Survey Commissoned Report*, CR/15/132. 95pp

VINCENT, C J. 2015. Maturity modelling of selected wells in the Central North Sea . *British Geological Survey Commissioned Report* CR/15/122. 184pp

General reference list

AMOCO (U.K.) PETROLEUM LTD. 1967 Final Well Log 38/16- 1. Downloaded from CDA.

ANDREWS, I J. 2013. The Carboniferous Bowland Shale gas study: geology and resource estimation. British Geological Survey for Department of Energy and Climate Change, London, UK

BEŁKA, Z., DEVLEESCHOUWER, X., NARKIEWICZ, M., PIECHA, M., REIJERS, T J A., RIBBERT, K-H. & SMITH, N J P., 2010. DEVONIAN.*IN:* DOORNENBAL, J.C. AND STEVENSON, A.G. (editors): *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE Publications b.v. (Houten): 71-79.

BESLY B M. 1998. Carboniferous. In *Petroleum Geology of the North Sea: Basic concepts and recent advances.* Glennie K W. (editor) p104-136. Oxford: Blackwell Science Ltd

BLACKBOURN GEOCONSULTING AND JOHN COLLINSON CONSULTING. 2006. The Occurrence, Petrography and Origin of Quartzitic Sandstones in the Namurian and Lower Westphalian of Quadrants 43 and 44, Southern North Sea. *Report.*. 216 pages . PDF available from BGS.

BREUNESE J., ANDERSON J., BRINKMAN S., JAGOSIAK P., KARNIN W., KARNKOWSKI P., KOMBRINK H., MESSNER J., MIJNLIEFF H., OLSEN S B., PERYT T., PISKE J., POPRAWA P., ROELOFSEN J., STOKER S., SMITH N., SWANN G., WAKSMUNDZKA M. AND VELDKAMP H. 2010. Appendix 3. *In:* (editors): *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE Publications b.v. (Houten): 305-314

BRUCE D R S. AND STEMMERIK L. 2003. Carboniferous. In *The Millennium Atlas: petroleum geology of the central and northern North Sea*. Evans D., Graham C., Armour A. and Bathurst P. (editors and co-ordinators) p83-89. London: Geological Society of London

CAMERON T D J., CROSBY A., BALSON P S., JEFFERY D H., LOTT G K., BULAT J. AND HARRISON D J. 1992a. Upper Permian. In *United Kingdom offshore regional report: the geology of the southern North Sea.* London: HMSO for the British Geological Survey: 43-54

CAMERON., CROSBY A., BALSON P S., JEFFERY D H., LOTT G K., BULAT J. AND HARRISON D J. 1992B. Lower Permian. In *United Kingdom offshore regional report: the geology of the southern North Sea.* London: HMSO for the British Geological Survey: 38-42

CAMERON, T D J. 1993a. 5. Carboniferous and Devonian of the southern North Sea. In: R. Knox and W. Cordey (Editors), Lithostratigraphical Nomenclature of the UK North Sea. *British Geological Survey.*

CAMERON, T D J. 1993b. 4. Triassic, Permian and Pre-Permian (Central and Northern North Sea) . In: R. Knox and W. Cordey (Editors), Lithostratigraphical Nomenclature of the UK North Sea. *British Geological Survey.*

CAMERON D., MUNNS J. & STOKER S. 2005. Remaining hydrocarbon exploration potential of the Carboniferous fairway. In: J. Collinson, D. Evans, D. Holliday and N. Jones (Editors), Carboniferous Hydrocarbon Geology: the southern North Sea and surrounding onshore areas. *Yorkshire Geological Society Occasional Publication Volume 7,* 209-224.

CENTRICA 2010. License relinquishment report, P1522 (Blocks 38/20, 38/25, 39/16 & 39/21) Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1522.pdf

CGG VERITAS 2011. Relinquishment Report for P1709, Block 38/4 Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1709.pdf

CHADWICK, R A., HOLLIDAY, D W., HOLLOWAY, S. & HULBERT, A G. 1995. The structure and evolution of the Northumberland–Solway Basin and adjacent areas. Subsurface memoir of the British Geological Survey.

CHURCH K D. & GAWTHORPE R L. 1994. High resolution sequence stratigraphy of the late Namurian in the Widmerpool Gulf (East Midlands, UK). *Marine and Petroleum Geology*, 11, 528-544

COLLINSON J, JONES C. AND IGI LTD. 1995. Source rock potential of the sub-Westphalian Carboniferous of the Southern North Sea. *Report and Appendix* 235 pages . PDF available from BGS.

COLLINSON, J., 2005. Dinantian and Namurian depositional systems in the southern North Sea. In: J. Collinson, D. Evans, D. Holliday and N. Jones (Editors), Carboniferous Hydrocarbon Geology: the southern North Sea and surrounding onshore areas. *Yorkshire Geological Society Occasional Publication Volume 7,* 35-56.

COLLINSON, J. AND JONES, C. 1997. Reservoir distribution and controls in the Dinantian and Lower Namurian of Quadrants 41, 42 and 43, Southern North Sea. *Report 97pp and 3 Appendices*. PDF available from BGS.

CONOCOPHILLIPS 2011 Licence Relinquishement Report UKCS Licences: P.1432 ; P. 1586 ; P.1587 Blocks 29/27, 29/28, 29/29, 37/3 and 37/4; P.1586 (Block 29/23) and P. 1587 (Block 29/30)) Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1432-p1586-p1587.pdf

CONWAY A M. & VALVATNE C. 2003. The Boulton Field, Block 44/21a, UK North Sea. In In Gluyas J G. and Hichens H M. (editors): *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume.* London: Geological Society Memoir, 20, 671-680.

DEA Group 2015 The Breagh offshore gas field. [Online] Available from: http://www.dea-group.com/en/projects/breagh [Accessed: November 2015]

Dolan P & Associates. 1994. New UKCS Gas Plays. Coals as Sources and Reservoirs. Commercial report and 3 Appendices.

EBN 2015a Poster from EAGE downloaded from the website https://www.ebn.nl/wp-content/uploads/2014/11/Poster4_EBN_EAGE2015_Dinant.pdf [Accessed 14/12/15]

EBN 2015b Poster from EAGE downloaded from the website https://www.ebn.nl/wp-content/uploads/2014/11/Poster6_EBN_EAGE2015_TectD.pdf [Accessed 14/12/15]

EDMONDS E A, MCKEOWN M C & WILLIAMS M. 1975. Britsh Regional Geology: Southwest England, 4th Edition British Geological Survey. HMSO London.

EXXONMOBIL 2010. Relinquishment Report for Licence P1259 Blocks: 36/15, 36/20, 36/25, 37/11, 37/16, 37/17, 37/18, 37/19, 37/20, 37/21, 37/22, 37/23, 37/24, 37/25, 38/16, 38/21, 38/22, 38/26, 38/27 and 38/28. Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1259.pdf

ERIKSEN S H., ANDERSEN J H., GRIST M., STOKER S. AND BRZOZOWSKA J. 2003. Oil and gas resources. In *The Millennium Atlas: petroleum geology of the central and northern North Sea*. Evans D., Graham C., Armour A. and Bathurst P. (editors and co-ordinators) p344-358. London: Geological Society of London

FARRIS M., ALLEN M. AND KING C. 2012 Central North Sea Palaeozoic, Sub-Salt Prospectivity, produced for Shell U.K. Limited

FRASER A J. & GAWTHORPE R L. 2003. An atlas of Carboniferous basin evolution in northern England. Geological Society of London, Memoir 28.

GAST, R E., DUSAR, M., BREITKREUZ, C., GAUPP, R., SCHNEIDER, J W., STEMMERIK, L., GELUK, M C., GEISLER, M., KIERSNOWSKI, H.,GLENNIE, K W., KABEL, S. & JONES, N S., 2010. Rotliegend. *In:* Doornenbal, J C. and Stevenson, A G. (editors): *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE Publications b.v. (Houten): 101-121.

GERLING P., GELUK M C., LOKHURST A., LOTT G.K. & NICOLSON R A. 1999. NW European Gas Atlas – new implications for the Carboniferous gas plays in the western part of the Southern Permian Basin. In Petroleum Geology of northwest Europe; proceedings of the 5th conference. A J Fleet and S A R Boldy (eds), 799-808. London: Geological Society.

GLENISTER I, SHELL/ESSO 2001 Forth Approaches 26/4a Prospect description.Downloaded from CDA

GLENNIE**,** K.W. & D.M.J. PROVAN. 1990 Lower Permian Rotliegend reservoir of the Southern North Sea gas province. In: Brooks, J. (ed) Classic Petroleum Provinces. Geological Society of London Special Publication, 50, 399-416.

GLENNIE K W. 1998. Lower Permian – Rotliegend. In *Petroleum Geology of the North Sea: Basic concepts and recent advances.* Glennie K W. (editor) p137-173. Oxford: Blackwell Science Ltd

GLENNIE, K., HIGHMAN, J. AND STEMMERIK, L., 2003. Permian. In: D. Evans, C. Graham, A. Armour and P. Bathurst (Editors). The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. *The Geological Society of London*, pp. 8-1: 8-44

GRANBY ENTERPRISES AND TGS-NOPEC. 2010. Relinquishment report P1315 Blocks 26/4a, 26/5, 26/9, 26/10a, 27/1a, 27/6a. Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1315.pdf

HALL P B. 1997 Geochemical Data Report Well UKCS 31/26a-12 Oils by Geolab Nor

HALLETT, D., DURANT, G.P. & FARROW, G.E. 1985. Oil exploration and production in Scotland. *Scottish Journal of Geology* 21: 547-570.

HAMPSON G J. 1997. A sequence stratigraphic model for deposition of the Lower Kinderscout Delta, an Upper Carboniferous turbidite fronted delta. *Proceedings of the Yorkshire Geological Society*, 51, 273-296.

HAMPSON G J., ELLIOTT T & DAVIES S J. 1997 The application of sequence stratigraphy to Upper Carboniferous fluvio-deltaic strata of the onshore UK and Ireland: implications for the southern North Sea. *Journal of the Geological Society of London*, 154, 719-733.

HAY S., JONES C M., BARKER, F. AND HE Z. 2005 Exploration of Unproven Plays; Mid North Sea High. Produced for EUPP Mid North Sea High Consortium, Report.

HAYWARD, R., MARTIN, C., HARRISON, D., VAN DORT, G., GUTHRIE, S. AND PADGET, N., 2003. The Flora field, blocks 31/26a, 31/26c, UK North Sea. Geological Society, London, Memoirs, 20(1), 549-555

HENDERSON S. 2013. Carboniferous- reservoir geology and development. PESGB training manual 'North Sea Petroleum Geology: exploration and production strategies in a mature hydrocarbon province' Part 4.

HODGE, T. 2003. The Saltfleetby Field, block L 47/16, licence PEDL 005, onshore UK. In: United Kingdom oil and gas fields commemorative Millennium Volume. *Memoirs of the Geological Society of London* , 20, 911-919

JONES N S, HOLLOWAY S, CREEDY D P, GARNER K, SMITH N J P, BROWNE, M.A.E. & DURUCAN S. 2004. UK Coal Resource for New Exploitation Technologies. Final Report. British Geological Survey Commissioned Report CR/04/015N.

JONES, N.S. 2007. The Scremerston Formation: results of a sedimentological study of onshore outcrop sections and offshore Well 42/13-2. British Geological Survey Commissioned Report, CR/07/101. 70pp

JONES C M. & CHISHOLM J I. 1997. The Roaches and Ashover Grits: sequence stratigraphic interpretation of a `turbidite-fronted delta' system, *Geological Journal*, 32, 45-68.

KOMBRINK, H., BESLY, B M., COLLINSON, J D., DEN HARTOG JAGER, D G., DROZDZEWSKI, G., DUSAR, M., HOTH, P., PAGNIER, H J M.,STEMMERIK, L., WAKSMUNDZKA, M I. & WREDE, V., 2010. Carboniferous. *In:* Doornenbal, J C. and Stevenson, A G. (editors):*Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE Publications b.v. (Houten): 81-99.

MARSHALL J E A. AND HEWETT A J. 2003. Devonian. In *The Millennium Atlas: petroleum geology of the central and northern North Sea*. Evans D., Graham C., Armour A. and Bathurst P. (editors and co-ordinators) p65-81. London: Geological Society of London

MARTIN, C. A., STEWART, S. A. AND DOUBLEDAY, P. A., 2002. Upper Carboniferous and Lower Permian tectonostratigraphy on the southern margin of the Central North Sea. *Journal of the Geological Society*, Vol. 159(6): 731-749.

MAYNARD J R & DUNAY R E. 1999. Reservoirs of the Dinantian (Lower Carboniferous) play of the Southern North Sea. In Petroleum Geology of northwest Europe; proceedings of the 5th conference. A J Fleet and S A R Boldy (eds), 729-45. London: Geological Society.

MILTON-WORSSELL R., SMITH K., MCGRANDLE A., WATSON J & CAMERON D. 2010. In (eds) Vining, B.A. & Pickering, S. C. The search for a Carboniferous petroleum system beneath the Central North Sea. Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference, 57–75. DOI: 10.1144/0070057

MONAGHAN, A.A. 2014. The Carboniferous shales of the Midland Valley of Scotland: geology and resource estimation. British Geological Survey for Department of Energy and Climate Change, London, UK

OFFSHORE-TECHNOLOGY, 2011. Breagh Gas Field, Southern North Sea, United Kingdom. [Online] Available from: http://www.offshore-technology.com/projects/breagh-field/ [Accessed: October 19th 2015]

OHM S E., KARLSEN D A., PHAN N T., STRAND T. & IVERSEN G. 2012. Present Jurassic petroleum charge facing Paleozoic biodegraded oil: Geochemical challenges and potential upsides, Embla field, North Sea. *AAPG Bulletin*, 96, 1523-1552.

O'MARA, P T., MERRYWEATHER M, STOCKWELL, M & BOWLER M. 2003. The Trent Gas Field, Block 43/24a, UK North Sea. In Gluyas J G. and Hichens H M. (editors): *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume.* London: Geological Society Memoir, 20, 835-849.

PA RESOURCES 2011. Relinquishment Report License P1318 23rd Round Promote UKCS Blocks 29/19a, 29/20b, 29/24, 29/25. Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1318.pdf

PA Resources 2009. Geophysical & Geological Evaluation of Blocks 29/20b, 29/20c,29/19a, 29/24 & 29/25 (Licences P1318, P1319), UK North Sea. Part 1. Company report in confidence (P. Copestake, G. Dunford, A. Billings, T. Wright, A. D. Carr).

PARSONS T. 2015. New plays in a mature basin: a review of the Lower Carboniferous on the southern margin of the Mid-North Sea High. Abstract and presentation at *Petroleum Geology of Northwest Europe conference*, 28-30 September 2015, London.

PERYT T M., GELUK M., MATHIESEN A., PAUL J. AND SMITH K. 2010. Zechstein. *In:* Doornenbal, J C. and Stevenson, A G. (editors): *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE Publications b.v. (Houten): 123-148

PHARAOH, T C, VINCENT, C J, BENTHAM, M S, HULBERT, A G, WATERS, C N, AND SMITH, N J. 2011. Structure and evolution of the East Midlands region of the Pennine Basin. *Subsurface memoir of the British Geological Survey*.

PLETSCH, T., APPEL, J., BOTOR, D., CLAYTON, C.J., DUIN, E J T., FABER, E., GORECKI, W., KOMBRINK, H., KOSAKOWSKI, P., KUPER, G.,KUS, J., LUTZ, R., MATHIESEN, A., OSTERTAG-HENNING, C., PAPIERNEK, B. & VAN BERGEN, F., 2010. Petroleum generation and migration. *In:* Doornenbal, J C. and Stevenson, A G. (editors): *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE Publications b.v. (Houten): 225-253.

PREMIER OIL 2008. Relinquishment Report P1229 License Blocks 42/10 and 42/15 Parts 1 and 2 Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1229-p1.pdf

ROC OIL 2005. Errington 1 Well results and formation evaluation. Onshore UK Northumberland Project Area PEDL028.

RODRIGUEZ K, WRIGLEY R, HODGSON N & NICOLLS H. 2014. Southern North Sea. Unexplored multi-level exploration potential revealed. *First Break*, 32, 107-113

RWE DEA 2011a. Relinquishment report Licence Number: P1524 42/2b, 42/3, 42/4. Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1524.pdf

RWE DEA 2011b Relinquishment report Licence Number: P1525 42/18. Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1525.pdf

SCHROOT B. M., V.BERGEN F., ABBINK O. A. , DAVID P., V.EIJS R, VELD H. 2006. Hydrocarbon potential of the Pre-Westphalian in the Netherlands on- and offshore - report of the Petroplay project. TNO report, NITG 05-155-C. Downloaded from the TNO website.

STONE, P., MILLWARD, D., YOUNG, B., MERRITT, J. W., CLARKE, S. M., MCCORMAC, M., AND LAWRENCE, D. J. D. 2010. British Regional Geology: Northern England (Fifth edition). (Keyworth, Nottingham: British Geological Survey).

SYMONDS R., LIPPMAN R., MUELLER B. AND KOHOK A. 2015. Yoredale Sandstone Architecture in the Breagh Field (UK SNS). Presentation for Sedimentology of Paralic Reservoirs: Recent Advances and their Applications. Geological Society Conference May 2015

SYMONDS R. 2015 The Breagh Field – A New Frontier in the Backyard. Presentation for Pitfalls, Peaks and Progress conference, Feb 2015.

TAGGART S. 2015. New opportunities on the northern feather-edge play of the Silverpit Basin: sedimentology and facies distribution of the Permian Lower Leman and Carboniferous Ketch Formations, Cygnus Field, Southern North Sea. Abstract and presentation at *Petroleum Geology of Northwest Europe conference*, 28-30 September 2015, London

TAYLOR J. C. M. 1998. Upper Permian – Zechstein. In *Petroleum Geology of the North Sea: Basic concepts and recent advances.* Glennie K W. (editor) p174-211. Oxford: Blackwell Science Ltd

TUCKER, M. E., GALLAGHER, J., LEMON, K., AND LENG, M. 2003. The Yoredale Cycles of Northumbria: High-Frequency Clastic-Carbonate Sequences of the Mid-Carboniferous Icehouse World. *Open University Geological Society Journal*, Vol. 24, 5–10.

UNDERHILL J. R. 2003. The tectonic and stratigraphic framework of the United Kingdom's oil and gas fields. In Gluyas J G. and Hichens H M. (editors): *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume.* London: Geological Society Memoir, 20, 17-59

UNDERHILL, J.R., MONAGHAN, A.A. & BROWNE, M.A.E. 2008. Controls on structural styles, basin development and petroleum prospectivity in the Midland Valley of Scotland. *Journal of Marine and Petroleum Geology* 25: 1000-1022

WINTERSHALL 2010. Licence Relinquishment Report P1129 (Blocks 41/5a, 41/10a and 42/1a). Downloaded from https://itportal.decc.gov.uk/web_files/relinqs/p1129.pdf

Appendix 1 Carboniferous timescale

This chart is reproduced from HOLLIDAY D W. & MOLYNEUX S G. 2006. Editorial statement: new official names for the subsystems, series and stages of the Carboniferous System – some guidance for contributors to the Proceedings. *Proceedings of the Yorkshire Geological Society*, 56, 57-58. Published with permission of the Yorkshire Geological Society

STANDARD DIVISIONS			REGIONAL DIVISIONS (W. Europe)		OBSOLETE TERMS
Sub System	Series	Stage	Stage	Substage	
PENNSYLVANIAN	UPPER	Gzhelian	Autunian (*pars*)	Kuzel	SILESIAN (UPPER CARBONIFEROUS)
			Stephanian	Stephanian C	
		Kasimovian		Stephanian B	
				A Barruelian	
				Cantabrian	
	MIDDLE	Moscovian	Westphalian	D Asturian	
				C Bolsovian	
	LOWER	Bashkirian		B Duckmantian	
				A Langsettian	
			Namurian	Yeadonian	
				Marsdenian	
				Kinderscoutian	
				Alportian	
GSSP	GSSP	GSSP		Chokierian	
MISSISSIPPIAN	UPPER	Serpukhovian		Arnsbergian	
				Pendleian	
	MIDDLE	Visean	Visean	Brigantian	DINANTIAN (LOWER CARBONIFEROUS)
				Asbian	
				Holkerian	
				Arundian	
				Chadian	
	LOWER	Tournaisian	Tournaisian	Courceyan: Ivorian	
GSSP	GSSP	GSSP		Courceyan: Hastarian	

Fig. 1. Chart showing recently ratified global subdivisions of the Carboniferous System and their approximately regional equivalents currently adopted in western Europe, derived from a wide variety of sources. Note that the former western European series are now regarded as stages, and the former stages as substages. Many of the subdivisions shown have not yet been fully formally defined, and in several instances the correlations of series and stage boundaries shown are presently approximate or uncertain. For example, the base of the Chadian substage does not precisely coincide with the base of the Visean, and the precise level of the base of the Kasimovian has yet to be decided.