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Palaeozoic Petroleum Systems of the Orcadian Basin to Forth Approaches, Quadrants 6-21, UK

Energy and Marine Geoscience Programme

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BRITISH GEOLOGICAL SURVEY

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Palaeozoic Petroleum Systems of the Orcadian Basin to Forth Approaches, Quadrants 6 - 21, UK

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Front cover

Core photograph of the Devonian Struie Formation from well 12/27- 1, 3027.3-3028.5 m

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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 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. Seismic companies (CGG Veritas, PGS, Spectrum, TGS, Schlumberger/WesternGeco) are thanked for allowing reproduction of selected seismic lines and for agreeing to the release of a set of 5 km resolution grids. CGG Veritas are also thanked for copy of 'Robertson Research International, 2001' and for use of selected LAS files.

Jim Ritchie (LR Senergy) and Christian Mathieu (OGA) are thanked for technical review of this report.

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Summary

This report synthesises the results of the 21CXRM Palaeozoic project to describe the Carboniferous and Devonian petroleum systems of the Orcadian Basin to Forth Approaches area (Quadrants 6 – 21).

Petroleum systems of the Orcadian study area that involve significant Palaeozoic elements are not wholly contained within Devonian, Carboniferous and Permian strata. A number of producing fields attest to two main proven petroleum systems;

i. *Co-sourced Devonian oil (with Jurassic oil) within a Jurassic reservoir*: the Beatrice, Jacky and Lybster fields;
ii. *Jurassic-sourced oil in a Devonian and/or Carboniferous reservoir*: the Buchan, Stirling, Claymore, Highlander fields. (Jurassic-sourced oil in a Permian (Zechstein) reservoir is also proven in the Carnoustie, Ettrick and Claymore fields, and in a Rotliegend reservoir in the Dee discovery).

A number of additional unproven petroleum system elements are considered in this report;

i. Possibilities for *Devonian and Carboniferous sourcing or co-sourcing* (with Jurassic oil) of *Devonian, Carboniferous and Permian (Rotliegend) reservoirs* in those areas underlain by proven Palaeozoic source rock;
ii. Possibilities for *migrated Jurassic and/or Devonian and/or Carboniferous hydrocarbons* onto horst blocks and the regional Grampian High, into *basement, Palaeozoic or younger reservoirs.*

Focusing on frontier areas north and east of the Inner Moray Firth and from the north-eastern Forth Approaches to Grampian High, integration of a large volume of seismic, well, geophysical, organic geochemistry, maturity and reservoir property data at regional scale has established:

Source rocks

- A wide extent of potential Devonian lacustrine source rocks mapped seismically from the Inner Moray Firth to the East Orkney Basin and north of the Halibut Horst.
- Geochemically-typed Devonian-sourced oil shows, oil seep data outside the area of mature Kimmeridge Clay Formation, burial depth and a limited organic geochemistry/maturity dataset indicative of Devonian source rocks that are potentially mature for oil generation outside the Inner Moray Firth.
- Good quality gas- and oil-prone Carboniferous source rocks are mapped from the Witch Ground Graben to north eastern end of the Forth Approaches. Wells drilled on highs indicate oil-window thermal maturity levels. Oil and gas shows and basin modelling indicate Carboniferous strata buried more deeply in adjacent basins may reach gas maturity levels, with Cenozoic maturation.
- Key source rock intervals are:
    - Lower Devonian, lacustrine Struie Formation (Quadrants 11, 12), oil prone.
    - Middle Devonian, lacustine Orcadia Formation and Eday Group (Quadrants 11-15 and possibly Quadrants 19, 20), oil prone.
    - Visean – Namurian (lower-mid Carboniferous) fluvio-deltaic Firth Coal Formation, gas and oil prone. (This unit is age-equivalent of the Scremerston and Yoredale Formations, Cleveland Group source rocks in Quadrants 25-44)

Reservoir rocks

- The Upper Devonian Buchan Formation and sandstones within the Carboniferous Firth Coal Formation form reservoirs in the Buchan, Claymore and Stirling oil fields. Porosities are moderate-low. Low permeabilities are enhanced by natural fractures.
- More widely, core data and petrophysical studies have highlighted possibilities for reservoir quality sandstones within the Devonian Middle Eday Sandstone and Upper Strath Rory formations of the Inner Moray Firth. The reservoir characteristics of the Upper Devonian Buchan Formation and sandstones within the Carboniferous Firth Coal and Fell Sandstone formation successions are locally variable, but regionally offer a thick and spatially extensive reservoir potential.

Sealing, trapping, migration

- Potential seal rocks vary across the study area.
    - Intraformational Devonian and Carboniferous seals remain untested.
    - In southern parts of Quadrants 20, 21 a Zechstein evaporite seal is likely to be effective
    - In other areas, post-Palaeozoic seals such as Jurassic and Cretaceous mudstones will be required to trap migrated Palaeozoic hydrocarbons
- A wide range of potential structural (faulted, folded) and stratigraphic (unconformity) traps are visible on seismic data
- Devonian source rocks are mature in the Inner Moray Firth. The structural complexity of the area together with limited maturity/geochemical datasets leads to uncertainty in timing of modelled maturation and migration. Late Cretaceous–early Cenozoic migration is modelled but a number of risks including possibilities for Palaeozoic migration/depletion and fault leakage to seabed exist.
- In the Devonian succession to the north of the Halibut Horst, and Carboniferous strata to the east of the Halibut Horst, a limited immature to oil-window thermal maturity level dataset from wells drilled on regional highs suggests limited generation at those locations, particularly within the gas-prone Carboniferous sequence. However, basin modelling on a Carboniferous ‘pseudo-well’ within the deeper basin (Quadrant 21) indicates gas maturity and generation may be attained.

Three Palaeozoic petroleum system elements are defined in this study; a Lower-Middle Devonian source and possible reservoir, an Upper Devonian reservoir interval, and Carboniferous source and reservoir rocks.

Based on the current dataset, the greatest potential for future prospectivity appears to be areas to the north, east and south-east of the Halibut Horst (Quadrants 14, 15, 20, 21). Here a combination of Devonian and Carboniferous source and reservoir rocks have potential for (i) Cenozoic-aged hydrocarbon generation from Palaeozoic source rocks and (ii) reservoir intervals with potential trapping geometries for migration of Palaeozoic oil/gas or Jurassic-sourced oil. Areas to the east and north of the current study area in Quadrants 8, 9 and 16 offer similar potential and require further study. Some parts of this area are heavily licensed; in these areas the Palaeozoic source and reservoir can be viewed as a stacked system offering additional, deep potential. The role of Palaeozoic structure on overlying Mesozoic and Cenozoic fields should also be further investigated to enhance future prospectivity.

Additional core and oil and gas geochemical data is required to better characterise the Palaeozoic petroleum system elements, e.g. additional maturity data for basin modelling. This particularly applies for maturation and modelling work in and east of the Inner Moray Firth and for possible migrated plays in the Grampian High area.

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. This report is the synthesis of project and previous work in the 'Orcadian study area' (Figure 1).

The lacustrine Devonian rocks of the Orcadian Basin have long been recognised as a source rock interval from studies of the seeps onshore, to advanced geochemical typing of oils from the Beatrice Field (e.g. Astin, 1990; Bailey et al., 1990; Robertson Research International, 2001; Marshall & Hewett, 2003 and references therein). Key to the petroleum potential of the Devonian source rock is the timing of maturation and migration in relation to Palaeozoic burial, Mesozoic and Cenozoic faulting, as well as in trap integrity (e.g. Hillier & Marshall, 1992; Marshall, 1998; Underhill et al., 2001).

This report utilises new seismic interpretation, well correlation, source rock geochemistry/maturity and oil and gas shows/typing data to further the evidence for a spatially extensive Devonian source rock interval extending to the east and north of the Inner Moray Firth. Critically, these areas are situated in areas where the Upper Jurassic Kimmeridge Clay source rock is largely immature or early mature for oil generation.

Upper Devonian and Carboniferous sandstones form an important reservoir interval in the Jurassic-sourced Buchan, Claymore, and Stirling oil fields. The reservoir character is reviewed and the wide spatial extent and structural setting of the sandstone units are documented in the context of potential Devonian-Carboniferous or Jurassic sourced hydrocarbons.

Palaeozoic source, reservoir and possible seal rocks only form a component of a multi-layered petroleum system across much of Quadrants 6 – 21, for example:

1. *Devonian co-sourced, Jurassic–reservoired systems* e.g. Beatrice Field Quadrant 11

2. *Jurassic-sourced, fractured Devonian and/or Carboniferous reservoir, Jurassic or Cretaceous mudstone seal* (e.g. Buchan, Quadrant 20/21; Stirling, Quadrant 16; Claymore, Quadrant 14)

Seals are provided at various levels within the Mesozoic succession with abundant opportunities for structural (faulted, folded) and stratigraphic (unconformity) traps.

Though detailed study of the Permian succession was out of scope, Permian reservoirs (Auk sandstone, Zechstein carbonates) and Zechstein evaporite seals provide a potential Palaeozoic play system in southern parts of the study area.

Recent interest in fractured basement plays was incorporated to potential migrated petroleum systems in the Grampian High area, such as evidenced by oil within granite fractures by the 'Bagpuss' well 13/24a- 2a.

The resources and time available to the Palaeozoic Project necessarily focussed on regional synthesis of the Devonian and Carboniferous intervals, whilst keeping the wider context and the role of Mesozoic and basement plays in mind.

The work undertaken in the Orcadian study area was prioritised from Sponsor feedback to:

1. provide a regional seismic-gravity interpretation of frontier areas (Figure 1; Arsenikos et al., 2016):
    a) Forth Approaches-West Central Shelf
    b) East Orkney Basin and beyond

c) Margins of the Grampian High

2. Undertake a source rock study on the evidence for migrated Devonian oils (Greenhalgh, 2016)
3. Provide consistent, regional Devono-Carboniferous stratigraphy and well correlations (Whitbread and Kearsey, 2016)

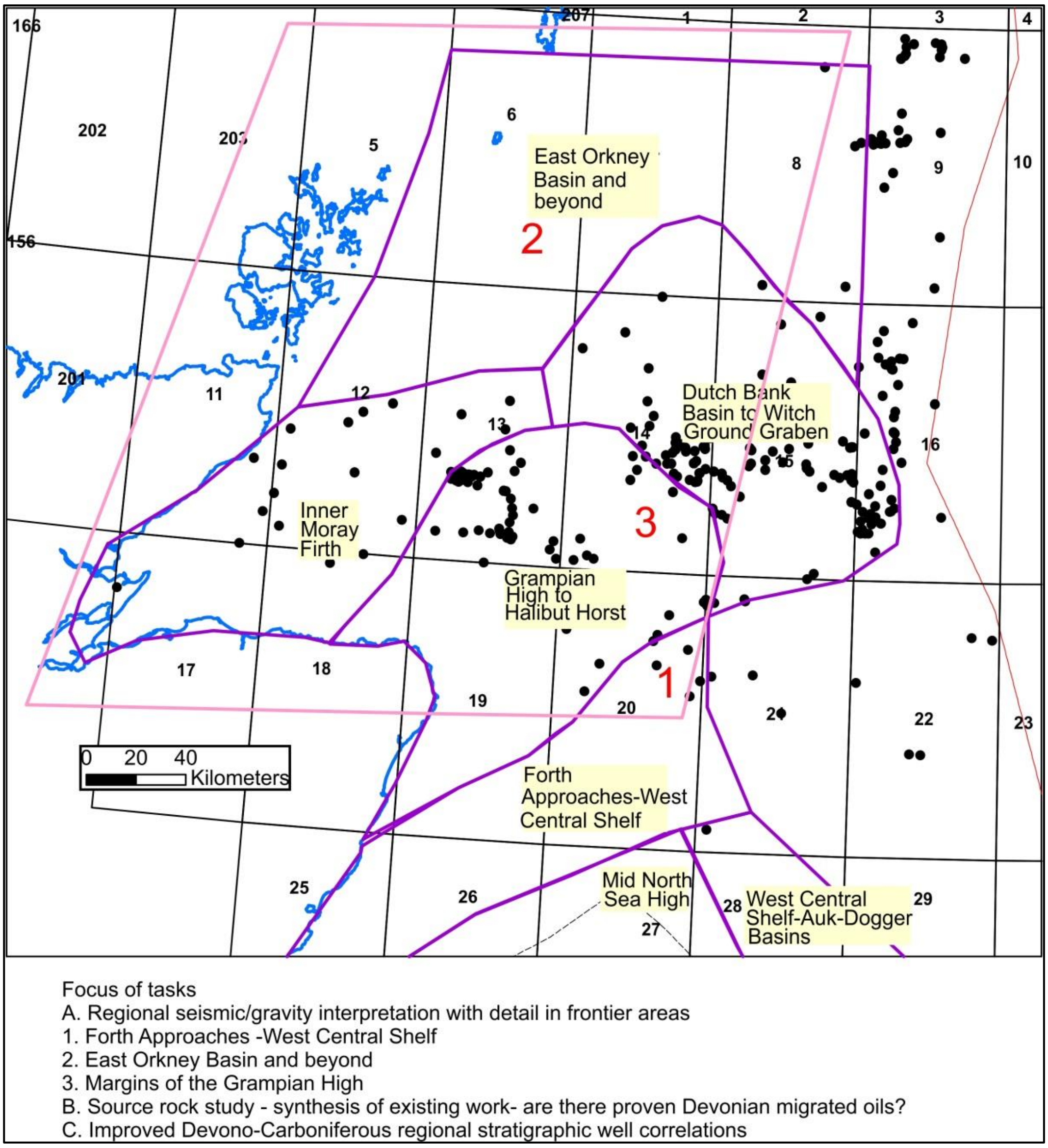


Figure 1 Extent of the Orcadian study area in pink and subdivision of Quadrants 6-21 to geological/petroleum system/data-defined sub-areas as described in the text. Red numbers indicate priority study areas ranked from Sponsor feedback.

The synthesis in this report is a *regional scale* synthesis of 21CXRM Palaeozoic Project studies (seismic: Arsenikos et al., 2016; wells/palaeogeography: Whitbread and Kearsey, 2016; gravity Kimbell and Williamson, 2016; tectonics, Leslie et al., 2016; reservoir petrophysics, Hannis 2016; source rock geochemistry and typing Vane et al., 2016 and Greenhalgh, 2016) 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. The report is structured to first give a regional overview and background, review evidence from the post-Permian succession, give detailed synthesis of the Inner-Outer Moray Firth and Grampian High study areas and finally to review the knowns and risks.

1.1.1 Interpretational confidence

It is clear from the seismic and well map shown on Figure 2 that data density is extremely variable across the study area. The vintage and quality of pre-Permian datasets is also variable, resulting in varying interpretational confidence across the areas studied. The areas with least data and lowest confidence are the East Orkney Basin-East Shetland Platform (Quadrants 6-8) and northeastern end of the Forth Approaches (Quadrants 19-21; Figure 2); the most data and highest confidence is for the Inner Moray Firth. Annotations and labels have been used on figures to describe and depict confidence in interpretations made during this study.

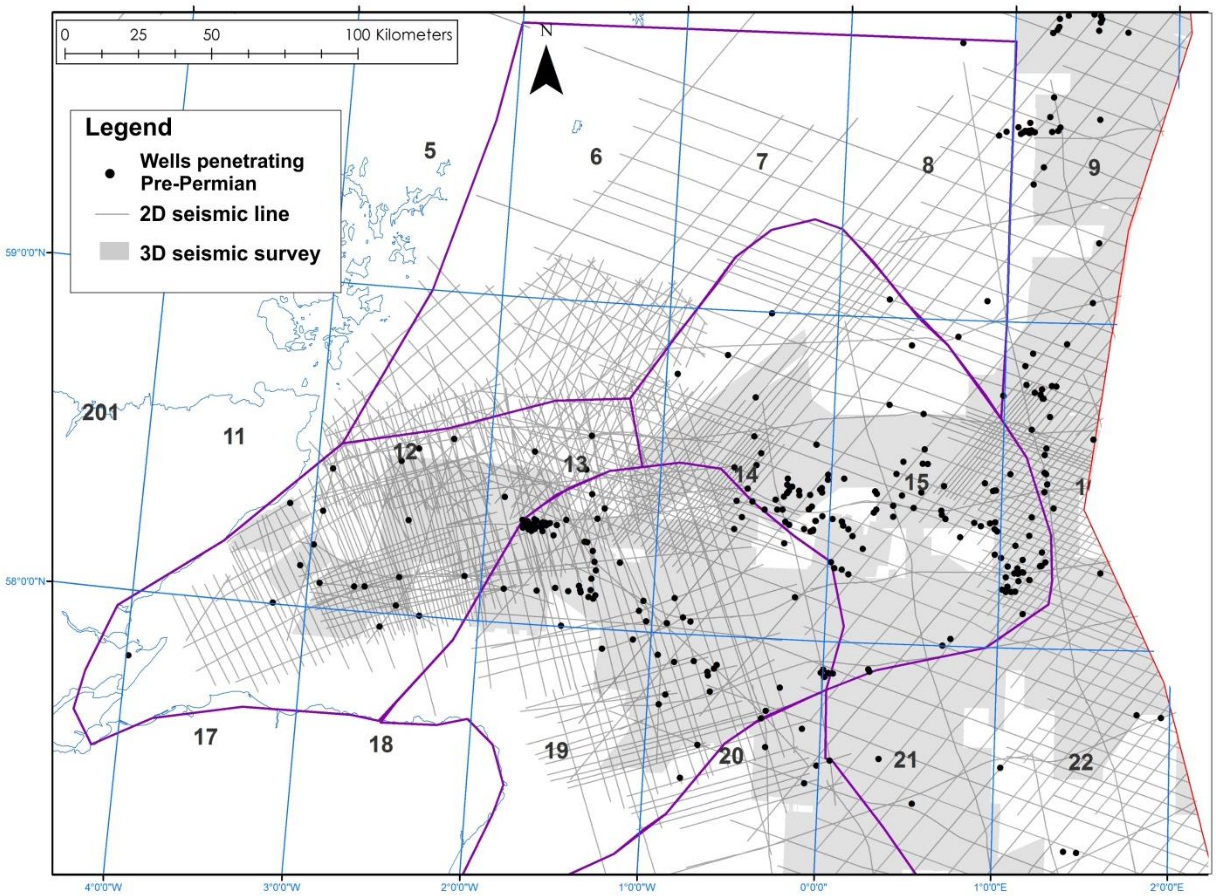


Figure 2 Data distribution across the Orcadian Study area. Wells penetrating the pre-Permian sequence are shown, though the length of pre-Permian penetration is extremely variable. 2D seismic data utilised and 3D seismic datasets consulted are shown (3D seismic was interpreted only in the northern parts of Quadrants 14 and 15).

2 Overview of Palaeozoic petroleum systems in Quadrants 6-21

Three Palaeozoic petroleum system elements can be defined within the Devonian and Carboniferous of Quadrants 6-21 (Figure 3). The ‘Lower–Middle Devonian source and possible reservoir’ comprises up to 3.5 km thick source rock intervals of the Struie, Orcadia formations and Eday Group, plus interbedded and laterally adjacent Devonian clastic, possible reservoir intervals. The ‘Upper Devonian reservoir’ of the regionally extensive Buchan Formation sandstone passes upwards to the ‘Carboniferous source and reservoir’ system composed of potential coal, oil shale and shale source rocks of the Firth Coal Formation. Channel sandbodies intercalated within the Carboniferous succession form reservoir intervals in the Claymore and Highlander fields (Harker et al., 1991; Whitehead and Pinnock, 1991).

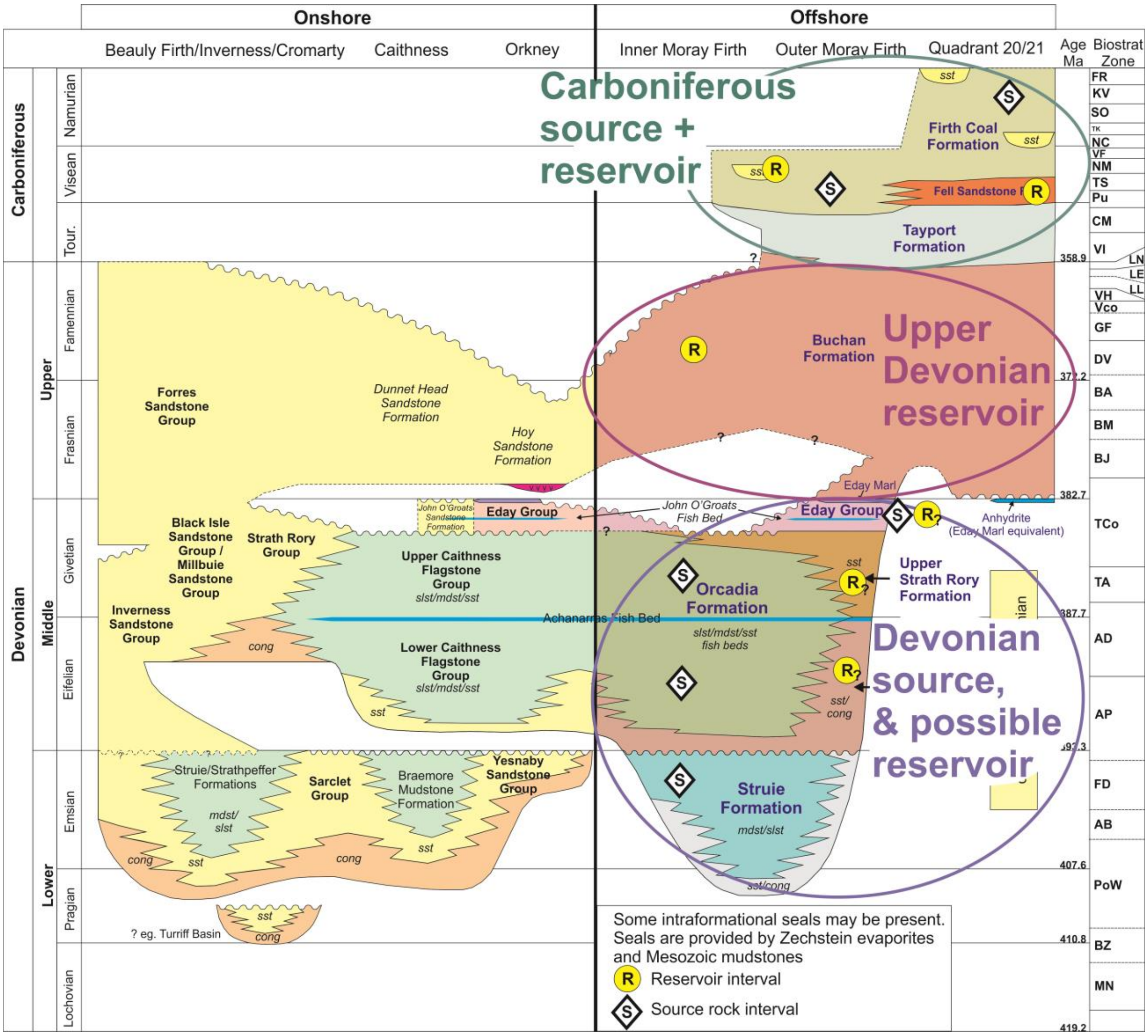


Figure 3 Simplified overview of Devonian-Carboniferous stratigraphy and petroleum system elements in Quadrants 6-21.

The spatial extent of the plays is controlled by both depositional extent and facies variations (e.g. Devonian lacustrine to clastic source rocks) and erosion at the latest Carboniferous-early Permian Variscan Unconformity (Figure 3). Facies variations and stratigraphical nomenclature are discussed in detail in Whitbread and Kearsey (2016; see also Figures 22, 26, 29, 33, 34).

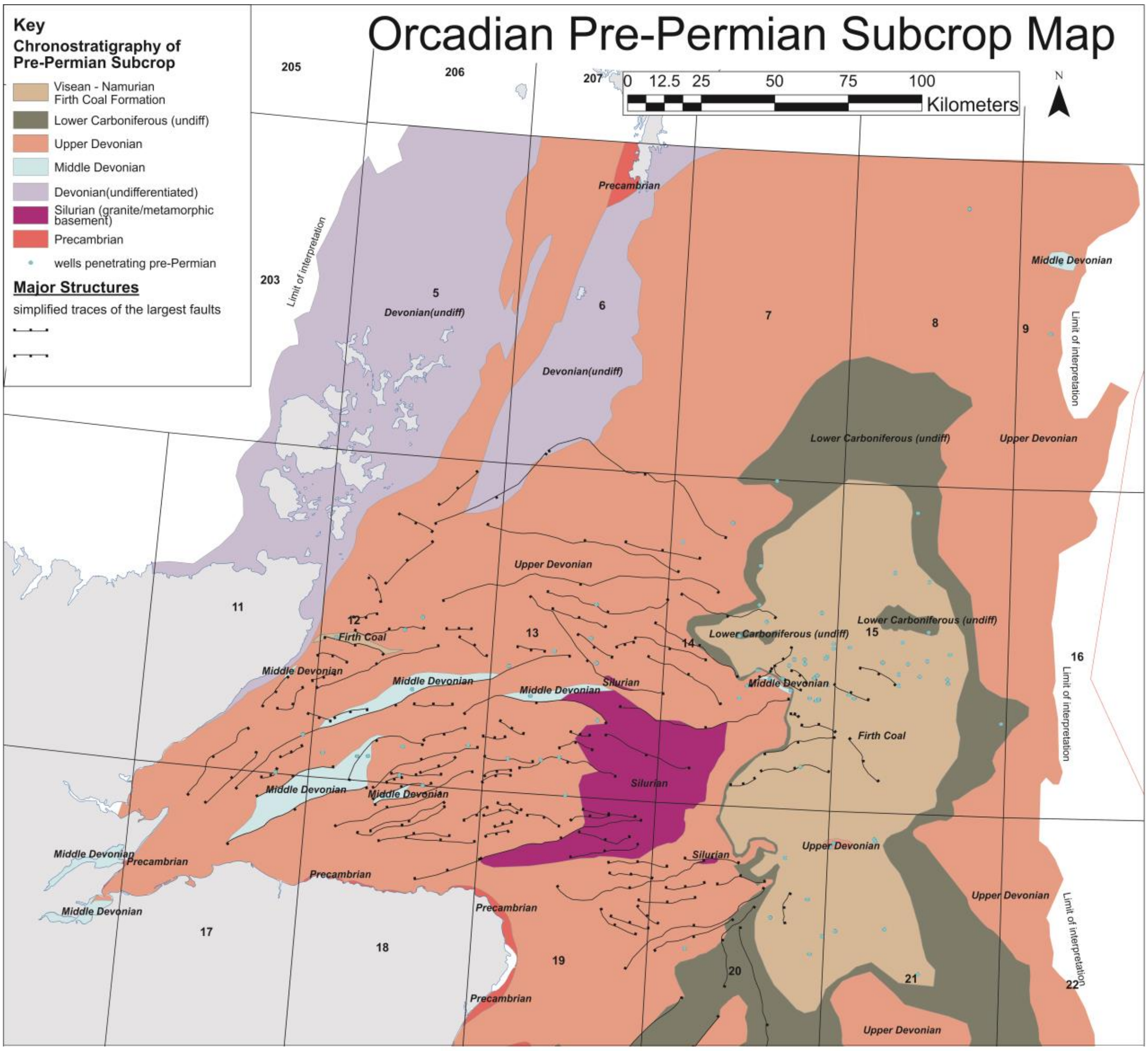


Figure 4 Pre-Permian subcrop map for the Orcadian study area based on integration of seismic interpretation and well correlations

Seismic and well inpretations have been incorporated to revise the pre-Permian subcrop map for the area (Figure 4). The subcrop map highlights Carboniferous strata running overall north-south in a series of basins across Quadrants 14, 15, 20 and 21 and joining with the poorly defined Lower Carboniferous successions at the north-eastern end of the Forth Approaches. The widespread extent of upper Devonian units across the Inner to Outer Moray Firth and over the Fladen Ground Spur and Viking/Central Graben rift shoulder is also dominant. The Grampian High-Grampian Spur-Halibut Horst, partially underlain by the South Halibut Granite forms a significant area of granitic and basement pre-Permian subcrop in Quadrants 13, 14, 19 and 20 ('Silurian' on Figure 4).

2.1 STRUCTURAL OVERVIEW

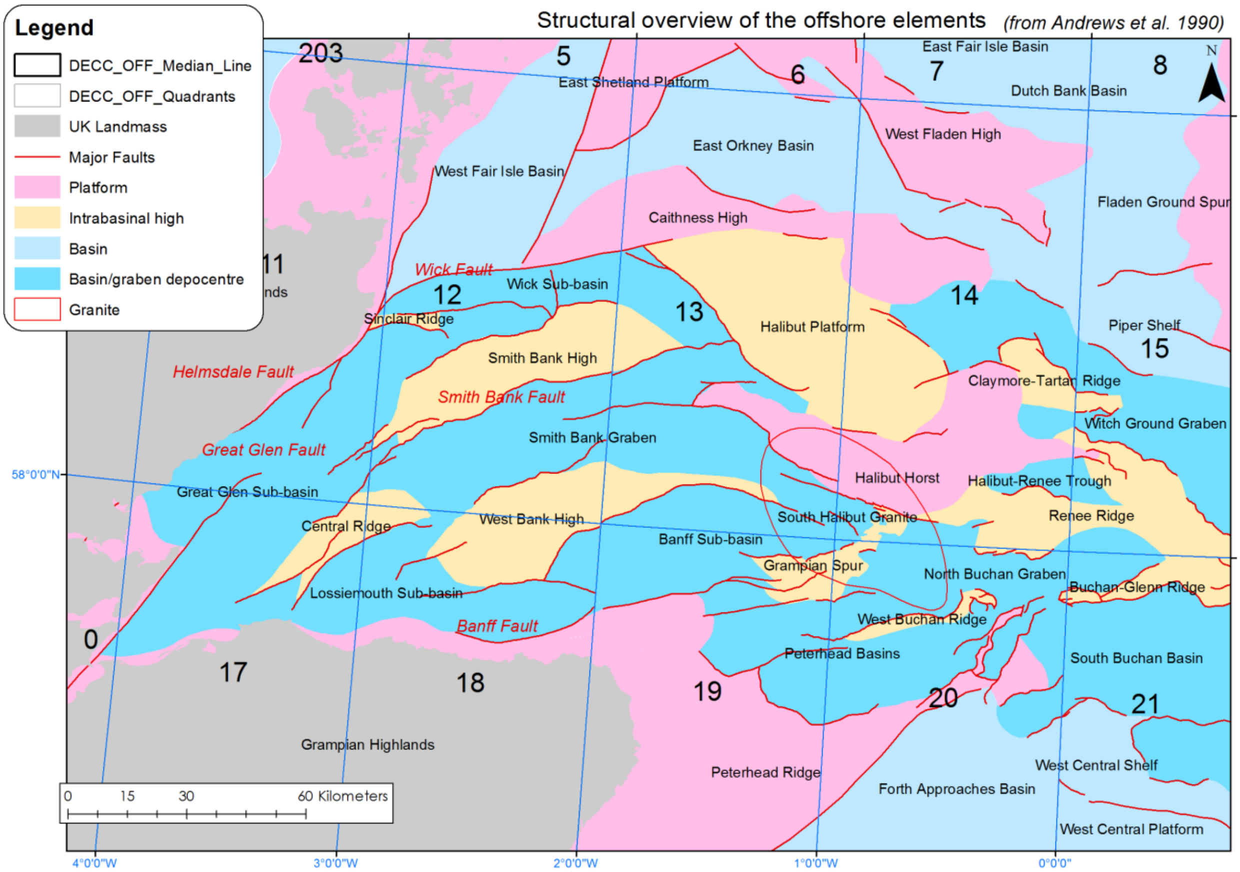


Figure 5 Structural diagram of the offshore domain illustrating the major structures in the study area (from Andrews et al., 1990).

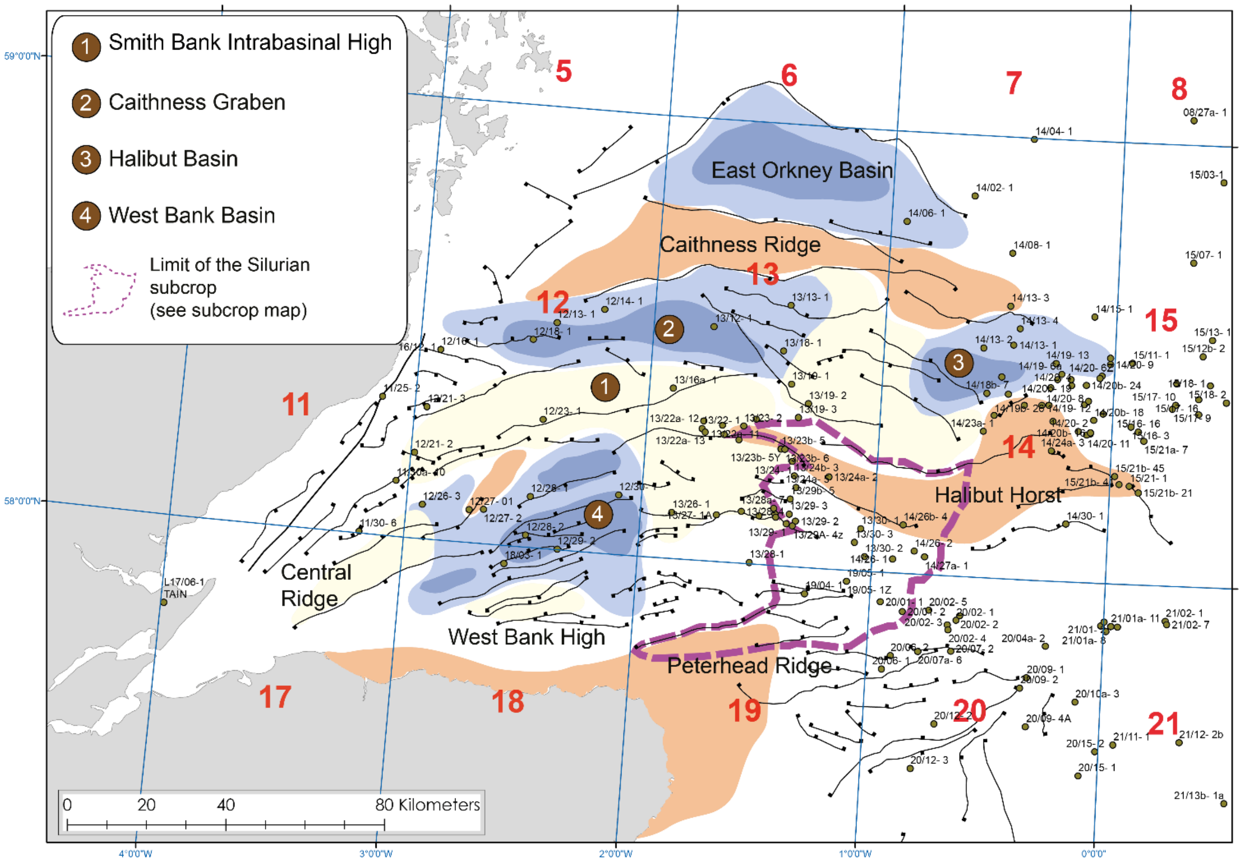


Figure 6 Structural diagram with the major Palaeozoic structural elements shown across the Inner Moray Firth and beyond. Blue areas are the basins/ depocentres, cream coloured are the terraces/ shelves and orange areas are the highs/ ridges from seismic mapping (Arsenikos et al., 2016).

Mesozoic faulting in Jurassic times (e.g. Thompson and Underhill, 1993) has strongly affected the current day fault pattern and dissected Palaeozoic depocentres. Cenozoic uplift and inversion, most prominent in the Inner Moray Firth (e.g. Hillis et al., 1994) also has an important impact in timing of burial/uplift and therefore maturity and migration. At regional scale, the dominant current day fault structures affecting the Palaeozoic succession can be simplified to three domains (Figures 5, 6)

- ENE to E trending half-graben and horst blocks in the Inner Moray Firth and north of the Halibut Horst/granite (Quadrants 11, 12, 13, 14 west)
- NW trending faulting to the northeast of the Halibut horst/granite, defining the Witch Ground Graben (Quadrants 14, 15)
- NE trending faulting at the northeastern end of the Forth Approaches , trending more to easterly faulting across the Grampian high and basinward (Quadrants 19, 20)

Areas further east across the Fladen Ground Spur and towards the Central/Viking graben rift shoulder (Quadrants, 9, 16) were not included within seismic interpretation for this study.

Beneath the Mesozoic and Cenozoic cover, the study area is crossed by Devonian-Carboniferous basins commonly at 1 – 5 km depth (Figures 5, 6, 23, 27, 35) filled by a dominantly fluvio-deltaic and lacustrine clastic sequence up to 3.5 km in thickness. The Carboniferous succession is thinner than comparable successions in the Central North Sea, reaching up to a maximum of around 600 m in wells (base not penetrated). The influence of granite-cored highs, particularly in the Halibut Horst-Grampian High area and underlying basement structure is a strong control on the overlying regional structure (see Leslie et al., 2016, Kimbell & Williamson, 2016).

2.2 EXTENT OF PETROLEUM SYSTEM ELEMENTS

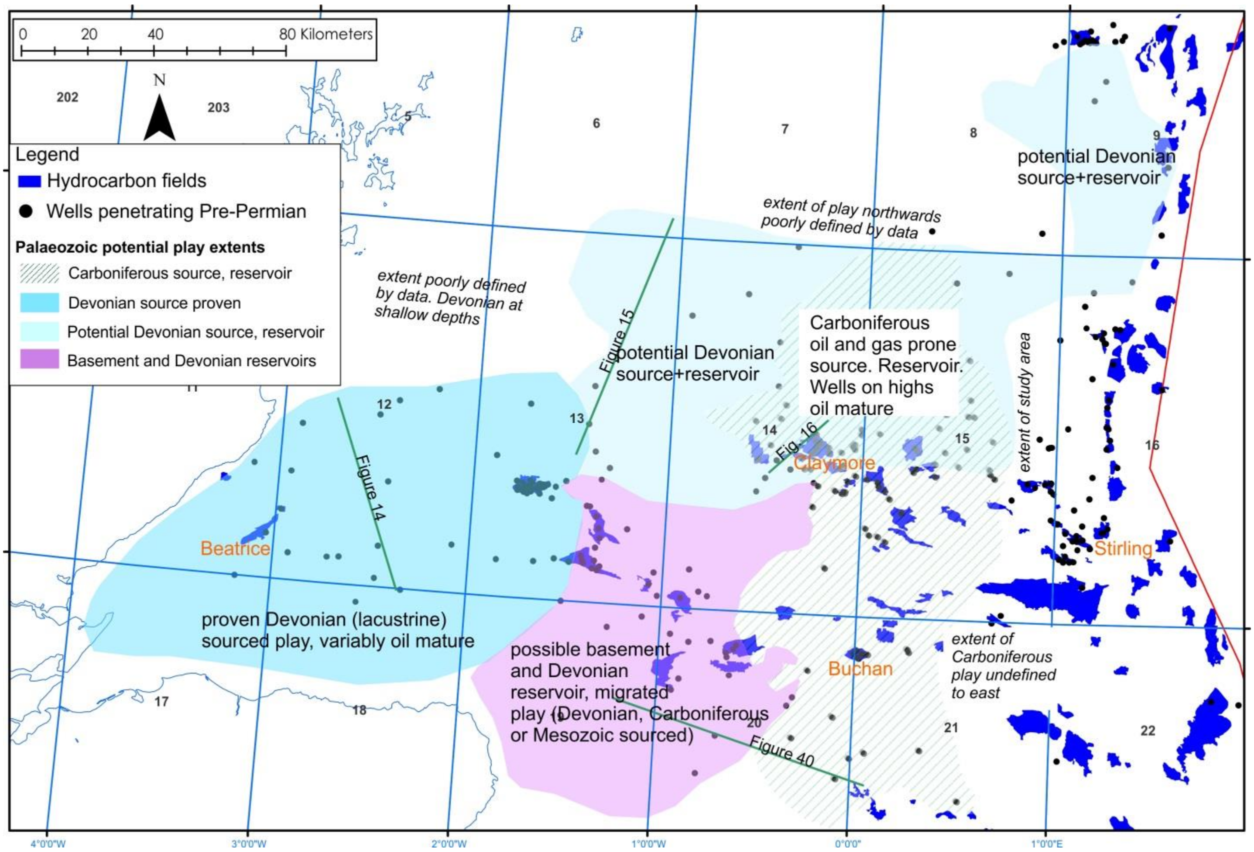


Figure 7 Approximate extent of Devonian and Carboniferous petroleum system elements in Quadrants 6-21. The approximate location of petroleum system cartoon Figures is shown.

Well and seismic interpretations have documented the wide extent of Devonian strata from onshore Scotland to Quadrants 9 and 16 (Arsenikos et al., 2016, Patruno and Reid, 2015), including, critically, the interpretation of lacustrine source rock intervals in wells in Quadrants 14 and 9 (e.g. Duncan and Buxton, 1995). This potential Lower-Middle Devonian source and Upper Devonian reservoir interval is shown on the darker and lighter blue areas of Figure 7. Together with new seismic mapping/inferred extent of the the potential Carboniferous source and reservoir intervals in the Firth Coal Formation (hatched), Figure 7 also illustrates the geographical extent of possible Upper Devonian or basement reservoirs around the Halibut Horst and Grampian High.

2.3 OIL AND GAS SHOWS

2.3.1 Devonian

Oil and gas shows data has been compiled from literature review and well records and supports a widespread extent of Devonian source and reservoir intervals (Figure 8). Geochemical typing of Devonian migrated oils is predominant in the Inner Moray Firth (Quadrants 11-13 west) but with two notable sample analysis much further east in Quadrants 14 and 15 (Robertson Research International, 2001). Oil shows and production within Devonian reservoir intervals in the Buchan, Stirling and West Brae fields are assumed to be Jurassic-sourced (Stevens, 1991; Gambaro and Currie, 2003). Roberston Research International (2001) document an isotopically light gas analysis from block 14/26 with derivation from a late mature source that they interpret as a possible indication of a late to post mature Devonian source kitchen in the vicinity of the Halibut Horst/North Buchan Graben.

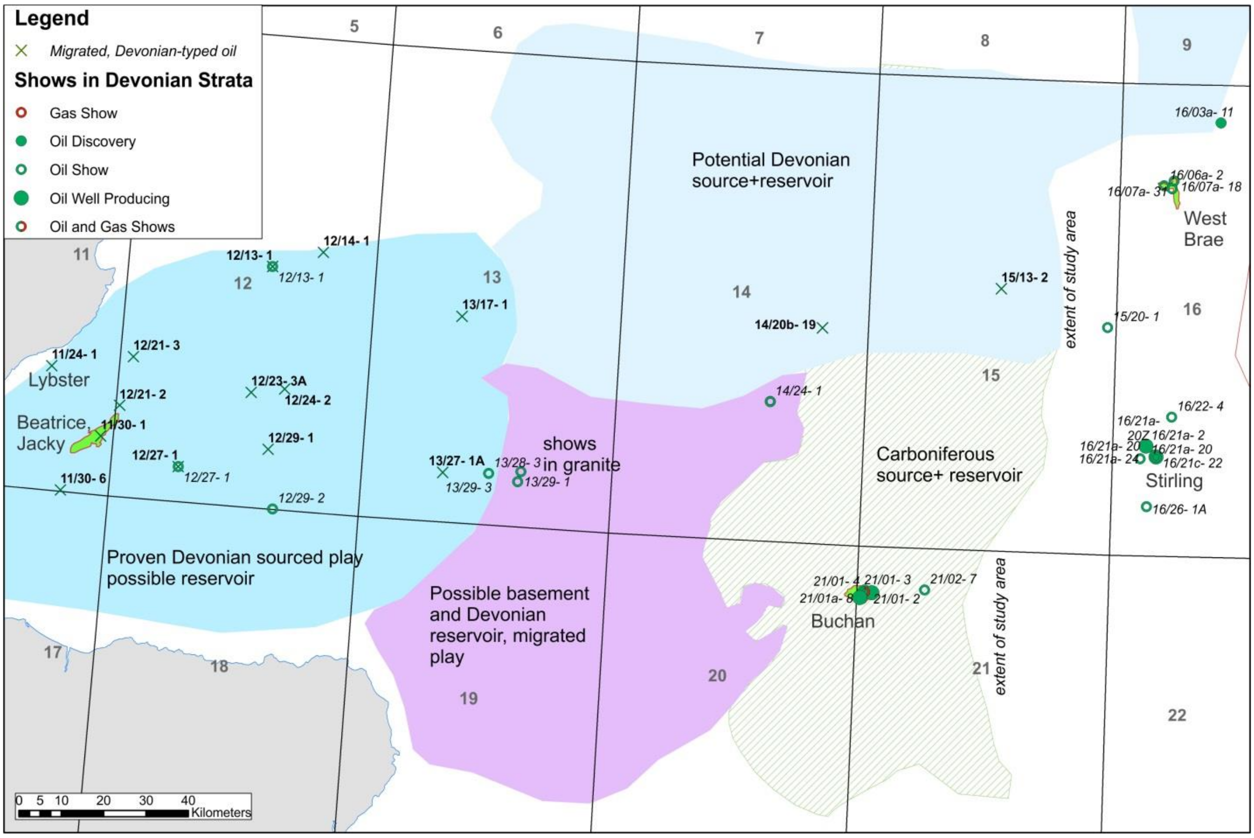


Figure 8 Map of shows, discoveries and fields containing a Devonian reservoir, or, a Devonian-typed source rock. Data compiled from well records and Robertson Research International (2001); Peters et al. (1999); Hewett (1993); Marshall (1998); The Geochem Group (1986); Curran (1987a).

2.3.2 Carboniferous

Both oil and gas shows and oil production occurs within Carboniferous reservoir intervals (Figure 9). Whilst oil production is believed to be Jurassic-sourced, the quality and oil-window maturity of Carboniferous source rocks does not preclude a contribution to oil shows. Gas level maturity of the gas-prone, coal-bearing Carboniferous source rocks (deeper into the basins than the wells drilled) is perhaps evidenced by gas shows within Carboniferous reservoir intervals (see section 5.4). Further geochemical and typing studies are required.

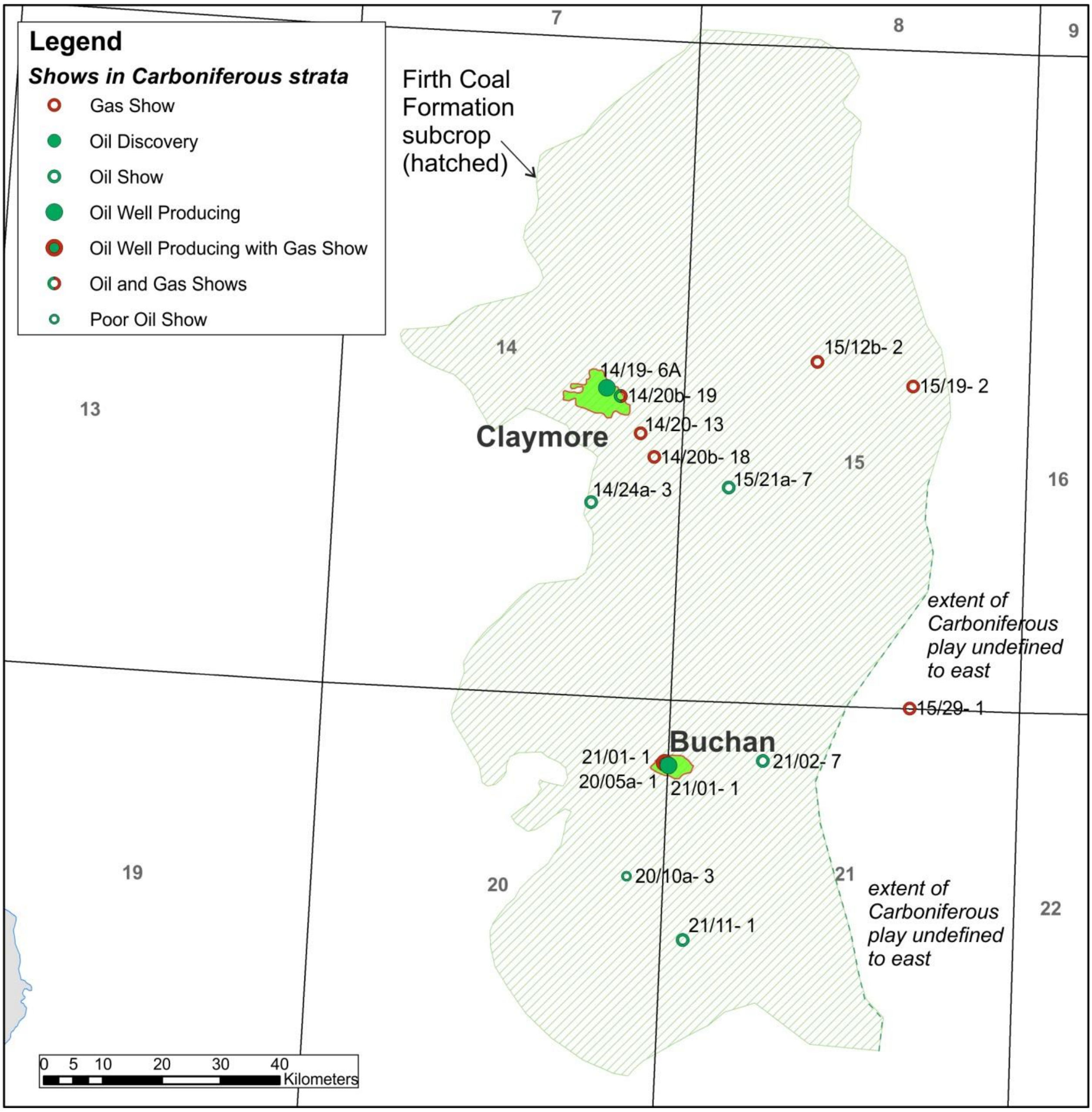


Figure 9 Map of shows, discoveries and fields within a Carboniferous reservoir, from well records and literature review. The Buchan and Claymore oil fields are believed to be Jurassic sourced (Edwards, 1991; Harker et al., 1991). Source rock typing studies were not located to determine any contribution of Carboniferous-Devonian source rocks in these fields.

2.4 SOURCE ROCK TYPE AND MATURITY

One of the key risks to Palaeozoic plays is the presence, quality, maturity and timing of maturation of source rock intervals. Compilation of Rock-Eval source rock geochemical data for Quadrants 6-21 gave a dataset of variable vintage, quality and well location (Vane et al., this study). Released data is available as an Excel spreadsheet to enable further analysis. The amount of released data compiled for this study was relatively small compared to the dataset available for the Central North Sea/Mid North Sea High (Vane et al., 2015).

At a regional, screening level, the released organic geochemistry data shows oil prone and variably oil-mature source rocks within the Devonian sequence. Carboniferous samples indicate gas- and oil-prone source rocks that are at immature to oil-window thermal maturity levels (Figure 10). Commercial reports contain additional geochemical data on the lacustrine source rocks of the Inner Moray Firth (e.g. Robertson Research International, 2001). Source rock quality and maturity is discussed in more detail in sections 4.3 and 5.3 below.

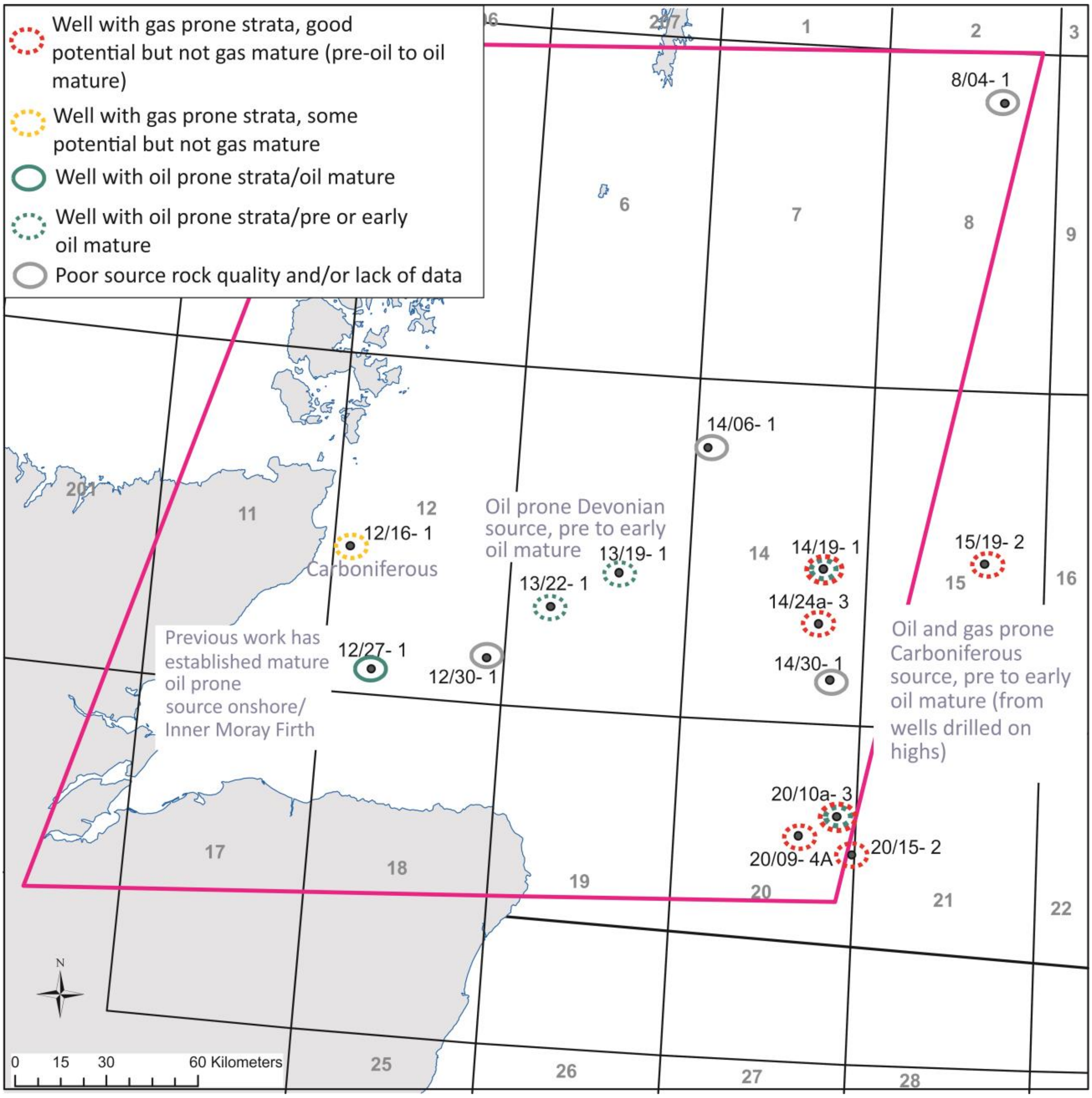


Figure 10 Summary map of organic geochemical/maturity screening results for Devonian and Carboniferous strata in the wells shown, from Vane et al. (2016).

2.5 MATURITY AND MIGRATION REGIONAL OVERVIEW

The two main proven source rocks of the Orcadian study area are of Devonian and Jurassic ages. The maturation history is complex, related to the regional tectonic regime.

Basin modelling studies suggest that onshore, the Devonian source rock experienced early hydrocarbon generation, reaching mid-late maturity by the Late Palaeozoic (Parkinson, 1983; Curran, 1987b, Keeley et al., 1990). Offshore, some maturation may have occurred in the most deeply buried Devonian source rocks (Hillier & Marshall, 1992). However in the Beatrice Field kitchen area, Mesozoic generation is modelled with the onset of oil generation from the Devonian lacustrine source rocks in the Early Cretaceous (Robertson Research International, 2001).

The Variscan Orogeny caused uplift, erosion and dyke injection within the Moray Firth basins during the Late Carboniferous, followed by a phase of subsidence during the Permian to Triassic period (Andrews, 1990; Marshall & Hewett, 2003). During the Early to Middle Jurassic a thermally induced crustal dome inflated and collapsed around the Forties Volcanic Province, which was followed by crustal extension and the formation of half-grabens during the Late Jurassic (Underhill and Partington, 1993). During this time the younger Devonian source rocks were sufficiently buried to a point where expulsion of hydrocarbons could begin to take place (Curran, 1987b). Regional thermal subsidence took place during the Early Cretaceous and into the Cenozoic, particularly within the Outer Moray Firth Basin (Robertson Research International, 2001; Marshall & Hewett, 2003 and references therein). During the Late Cretaceous, generation of hydrocarbons from the key source rock of the Kimmeridge Clay Formation began as the deposits were sufficiently buried in eastern parts of the study area. This continued until Cenozoic uplift began (Curran, 1987). The Inner Moray Firth Basin experienced a major period of uplift and eastwards tilting during the Palaeocene to Early Eocene, which exceeded 1 km within the west of the basin, decreasing eastwards to near zero (Hillis et al., 1994).

Migration of Palaeozoic-sourced hydrocarbons generated in the Mesozoic may have occurred into Mesozoic reservoirs and traps (e.g. as is believed to have occurred in the Beatrice Field). However there are several risks to Palaeozoic hydrocarbon sourcing, migration and accumulation including:

- Early depletion of source rock due to Devonian and Carboniferous maturation (Hillier & Marshall, 1992)
- Variable maturity and migration histories dependent on local block-basin structural configurations.
- Breach of Palaeozoic traps by Variscan inversion and Mesozoic faulting (Curran, 1987b; Marshall, 1998)
- Faults reaching seabed (in Inner Moray Firth and East Orkney Basin) and providing migration-escape routes for Mesozoic-recent generated hydrocarbon (Richardson et al., 2005, Underhill et al. 2001)
- Complex migration pathways to Mesozoic and younger reservoirs

The maturity and organic geochemistry dataset available limited new work undertaken for this study to selected 1D well-based case studies for a Devonian source rock in the Inner Moray Firth, and a Carboniferous source rock in the Buchan Basin, east of the Grampian High (Vincent 2016, see sections 4.4. and 5.4). A basin-wide study of hydrocarbon generation and migration was outwith the resources and dataset available and is recommended as future work.

3 Review of the relevant Permian and post-Palaeozoic petroleum system elements

3.1 OVERVIEW

Migration of Palaeozoic-sourced hydrocarbon to younger reservoirs and migration of Jurassic-sourced oil to Palaeozoic reservoirs necessitates a regional scale overview of salient post-Palaeozoic petroleum system elements.

3.2 FIELDS, DISCOVERIES

Fields involving a Palaeozoic component can be grouped as follows:

- *Evidence of Palaeozoic-sourced (Devonian) hydrocarbon within a Mesozoic reservoir*: the Beatrice and nearby Jacky and Lybster Fields.

- *Jurassic-sourced oil in a Devonian-Carboniferous reservoir*: the Buchan, Stirling, Claymore, Highlander Fields.
- *Jurassic-sourced oil in a Permian reservoir:* Fields including Carnoustie (Quadrant 22), Ettrick (Quadrant 20) and Claymore (Quadrant 14) are reported to contain a reservoir in Zechstein carbonates. In the Carnoustie Field the carbonates are described as vuggy and fractured (Glennie *et al.*, 2003). The Dee discovery (well 13/28- 4, northern margin of Banff sub-basin) incuded two oil bearing zones within Rotliegend sandstones, with a suggestion of possible Devonian co-sourcing (First Oil, 2009).

The fields with Devonian and Carboniferous component are described in more detail in sections 4.2 and 5.2.

The Buzzard Field (boundary Quadrants 19, 20) is also of note due to the up-dip migration of Kimmeridge Clay Formation sourced oil to an Upper Jurassic sandstone reservoir (Doré & Robbins, 2005). This structural configuration and migration pathway is of interest if applicable to the underlying Palaeozoic source rocks in this area.

Two examples of oil shows/discoveries within fractured granitic basement are relevant for their structural style and implications for migration pathways; 'Bagpuss' on the Halibut Horst (well 13/24a- 2a) and Cairngorm (block 16/3; Jenkins, online).

3.3 SOURCE ROCKS

The major source rock interval of the Upper Jurassic Kimmeridge Clay Formation is widespread across the study area (Figure 11). However, it is immature to early mature across much of the area under consideration (Figure 11). Prospectivity over much of the area therefore has to invoke either long-distance Jurassic migration or Palaeozoic-sourcing.

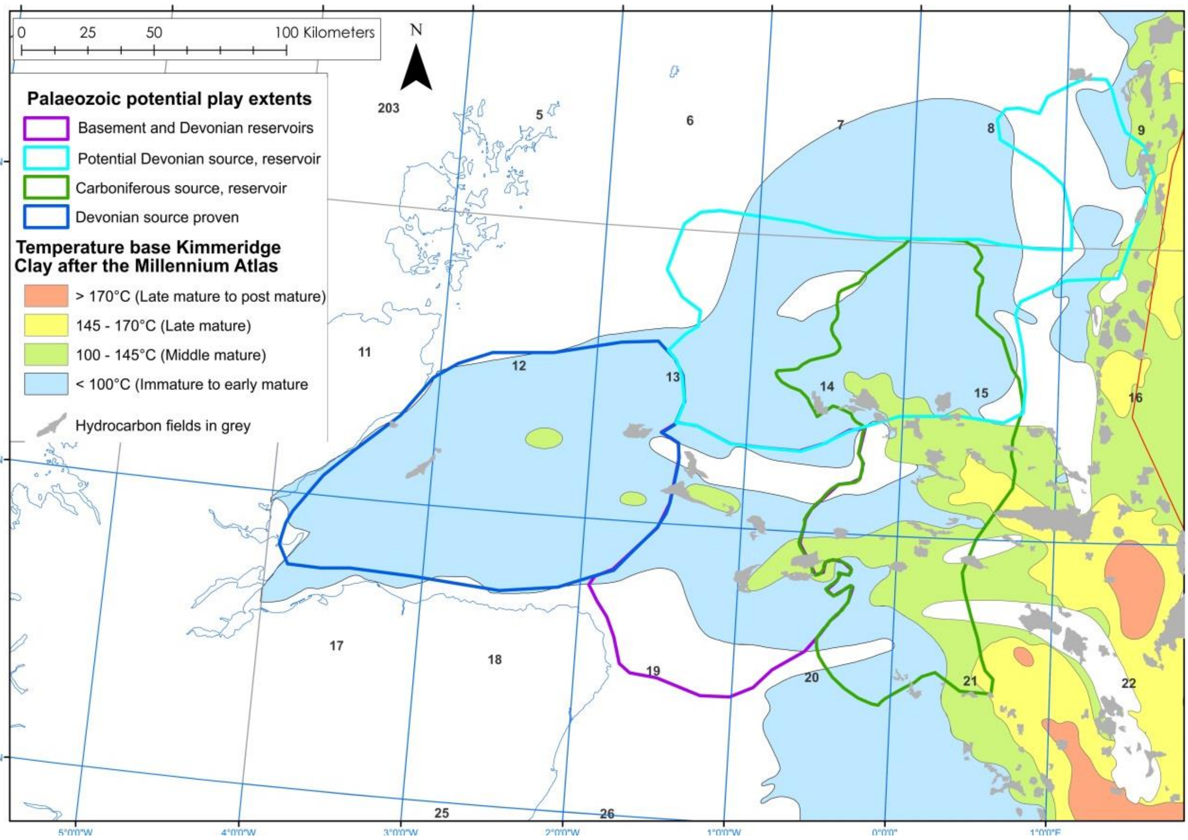


Figure 11 Map of the temperature and maturity level of the Kimmeridge Clay Formation from Kubala et al., (2003, fig. 17.12, reproduced with permission of The Geological Society, London), overlain by hydrocarbon fields (grey) and outlines of potential Palaeozoic petroleum system extents.

The Middle Jurassic Brora Coal Formation is also believed to be a source rock in Inner Moray Firth (Kubala et al., 2003). The organic-rich Permian Kupferschiefer Formation varies in thickness from 1 – 20 m, and is thought to be too thin to produce hydrocarbon accumulations of any economic value (Glennie et al., 2003).

3.4 RESERVOIR ROCKS

Permian Rotliegend Group sandstones form a major reservoir interval for Carboniferous-sourced gas fields in the Southern North Sea and are potential reservoirs in the study area. North of the Mid North Sea High, the Rotliegend Group is subdivided into the Auk, Fraserburgh and Findhorn formations (Figure 12; Glennie et al., 2003). Aeolian sandstones dominate the Auk Formation with occasional conglomerates. The Fraserburgh Formation comprises lacustrine or sabka siltstone and claystone deposits which interfinger with the Auk Formation. The Findhorn Formation deposits primarily comprise claystone and sandstone of fluvial, aeolian and lacustrine origin. Vuggy and fractured carbonate deposits of the Zechstein Group form the reservoir in the Carnoustie field (Quadrant 22) and oil was produced from drillstem tests on Zechstein dolomite beneath the Jurassic reservoir of the Ettrick Field (Glennie et al., 2003).

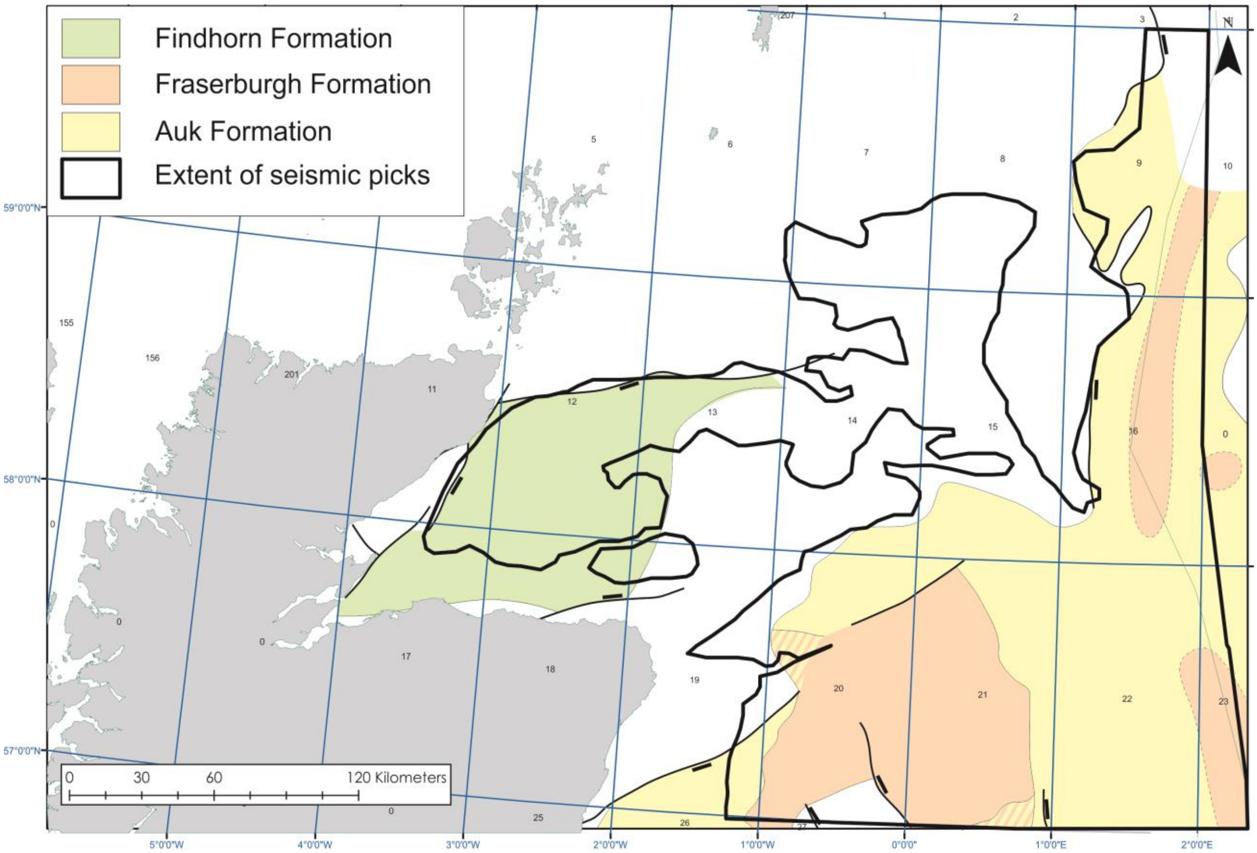


Figure 12 Generalised extent of Rotliegend Group units after Glennie et al. (2003, fig. 8.12; coloured extents, reproduced with permission of The Geological Society, London), and extent from new seismic mapping for this study, in black.

Reservoir intervals higher in the succession have the potential to host Palaeozoic-sourced hydrocarbons if the correct migration pathways and trapping geometries and in place. Examples include the Middle Jurassic Beatrice Formation in the Beatrice Field.

3.5 SEAL ROCKS

A regional top seal to Rotliegend, Carboniferous and Devonian reservoirs is provided by thick Zechstein evaporites at the north-east end of the Forth Approaches and southern Buchan Basin (Figure 13. Southern Quadrants 20, 21). Northwards, the succession is of variable thickness and facies (e.g. carbonate reservoir in the Carnoustie Field) and is a dominantly terrestrial clastic succession in the Inner Moray Firth (Figure 13).

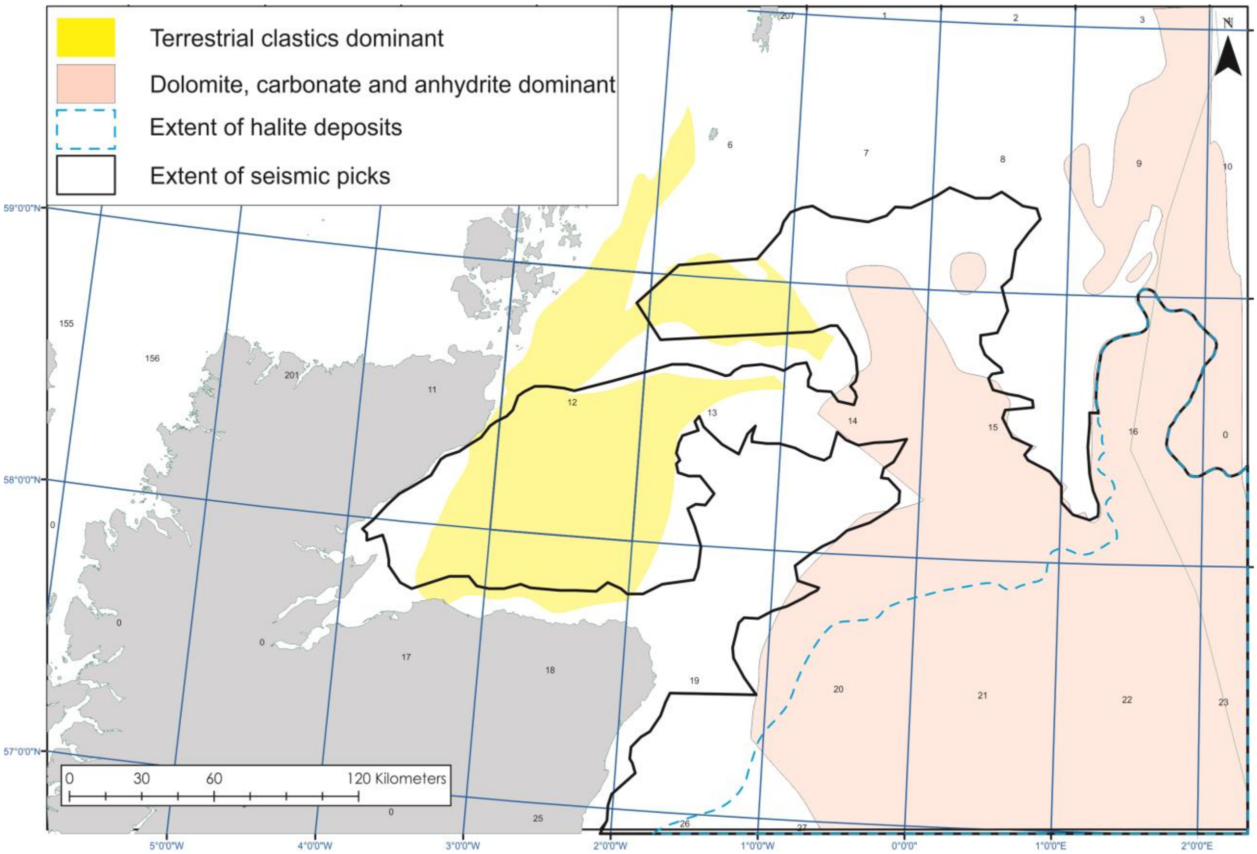


Figure 13 Generalised extent and units of the Zechstein Group, after Glennie et al. (2003, figs. 8.22, 8.23; coloured, reproduced with permission of The Geological Society, London), together with seismically mapped Zechstein extents (this study).

Within the Moray Firth basins, Upper Jurassic and Cretaceous mudstones also provide seals. For example the Buchan Field is sealed by Cretaceous mudstones (Edwards, 1991).

3.6 TRAPS

A wide variety of structural traps exist as a result of Mesozoic, particularly Jurassic, rifting. For example the Buchan oil field is a faulted Jurassic horst block (Edwards, 1991). The structural tilted-block highs that exist along the margins of the ESE-trending Witch Ground Graben, such as in the Claymore oil field (Harker et al., 1991), are another example (see section 4.2).

4 Results: Devonian and lower–mid Carboniferous petroleum systems of the Inner Moray Firth - Outer Moray Firth - East Orkney Basin

4.1 OVERVIEW

Three play cartoons (Figures 14, 15, 16) illustrate a number of features of the Devonian and Carboniferous petroleum systems over southern Quadrants 6 – 8 and Quadrants 11 – 15 (Inner Moray Firth, Outer Moray Firth and East Orkney Basin).

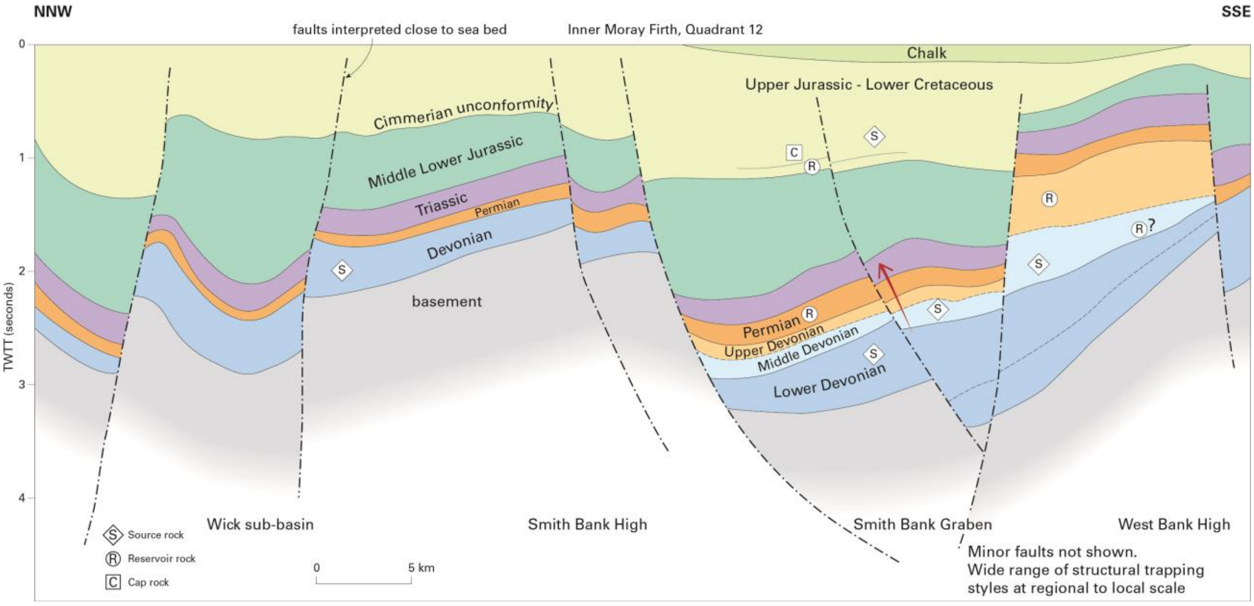


Figure 14 Cartoon of the Inner Moray Firth, Devonian play system. The red arrow indicates a hypothesized hydrocarbon migration pathway towards a geometry similar to that of the Beatrice oil field. The approximate location of the cartoon is shown on Figure 7.

The Inner Moray Firth play cartoon (Figure 14) illustrates the thick Lower-Middle Devonian source rock interval, and potential Upper Devonian and Permian clastic reservoir intervals, cut by Mesozoic faulting. Faulting and folding causes structural and stratigraphic (unconformity) traps. Migration from Devonian lacustrine source rocks to higher Jurassic reservoirs and fault-block traps, as is the case in the Beatrice Field, is indicated. Risks to prospectivity include faults interpreted close to sea bed which could facilitate escape of generated hydrocarbons (Underhill et al., 2001; Richardson et al., 2005). Note that a halite/anhydrite Zechstein seal is missing; the Zechstein Group is represented by a clastic facies in this area.

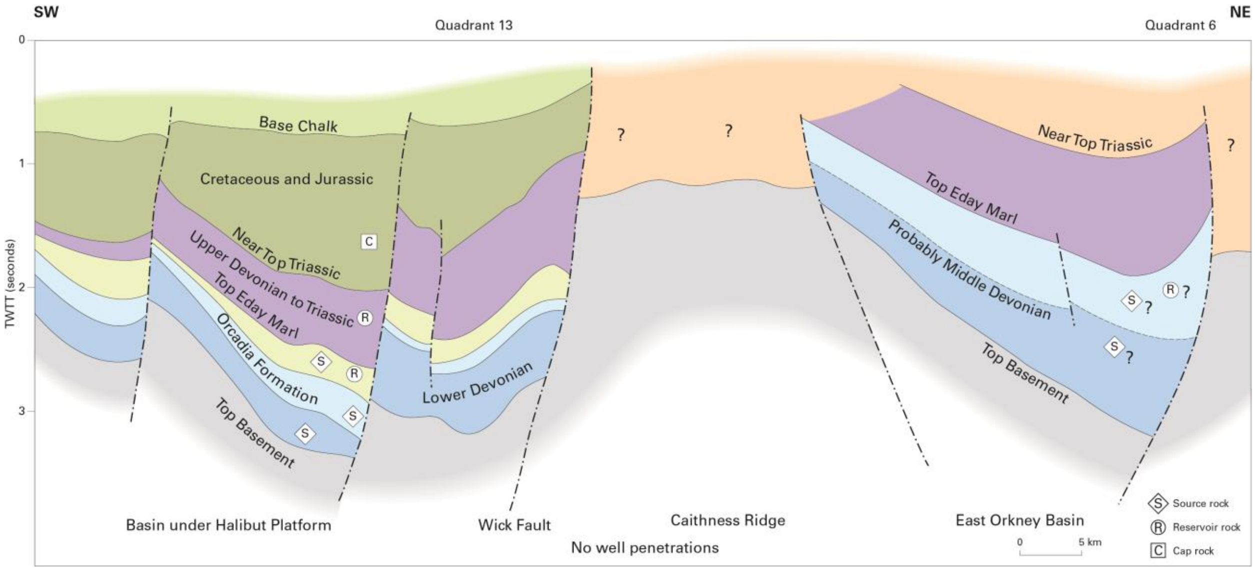


Figure 15 Cartoon of the Devonian play elements of the East Orkney Basin and the Halibut Basin (underlying the Halibut Platform) to the south of the Caithness Ridge. Seismic data resolution and lack of well control leads to uncertainty in the interpretation around the East Orkney Basin. The approximate location of the cartoon is shown on Figure 7.

The East Orkney Basin and Halibut Basin play cartoon (Figure 15) illustrates the thick Middle Devonian source rock intervals interpreted. Burial depths, and therefore likely maturity, are similar to those in the Inner Moray Firth. Possible reservoir intervals include sandstones within the Middle Devonian Eday Sandstone Formation and lateral equivalents of the Orcadia Formation. Structural traps, and possible seals within the Mesozoic succession of the Halibut Basin are envisaged. Hydrocarbon trapping potential in the East Orkney Basin is poorly resolved due to lack of well control and poor seismic definition on adjacent highs (Figure 15).

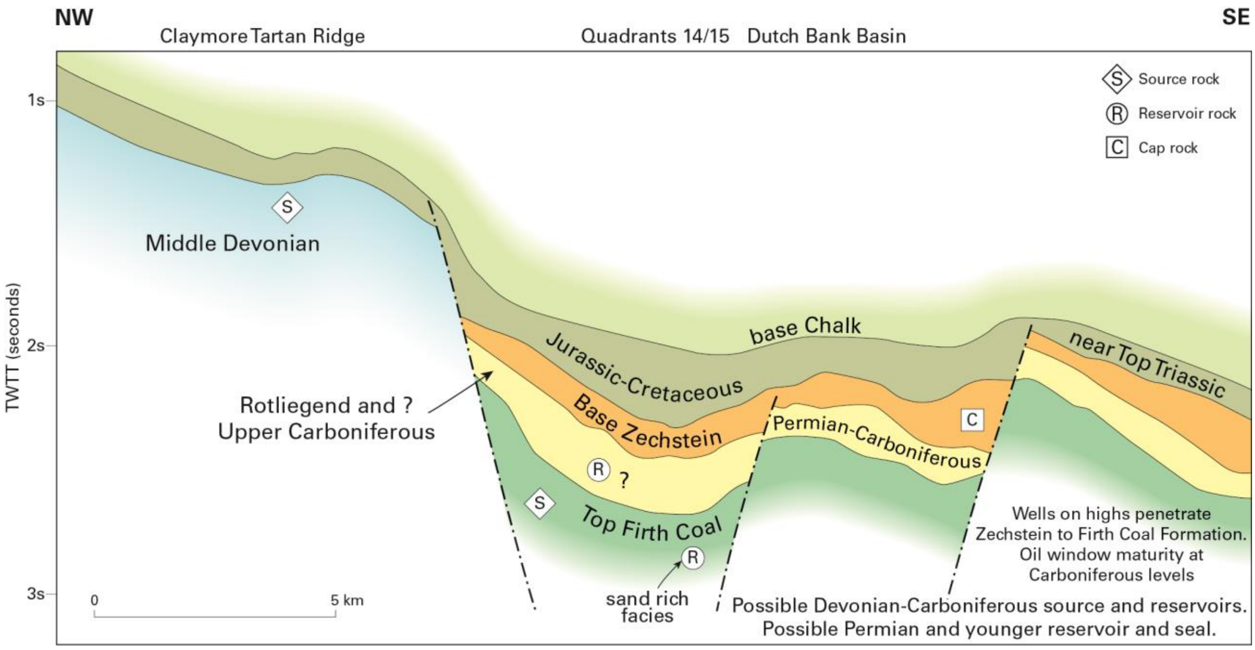


Figure 16 Cartoon of the Devonian and Carboniferous play elements in Quadrants 14 and 15. Facies variations (anhydrite, carbonate, dolomite) within the Zechstein interval control its sealing capacity. The approximate location of the cartoon is shown on Figure 7.

The Carboniferous Firth Coal Formation is a potentially important source and reservoir rock interval mapped in tilted fault-block graben and half-graben in Quadrants 14, 15 and proven in wells in Quadrants 20, 21 (Figure 16). Wells drilled on basinal highs prove good quality, dominantly gas-prone source rocks that are at oil-window maturity levels. Over 600 m of this unit is proven in some wells (base not penetrated). Opportunities for deeper burial and increased maturity are clear into the basins and oil and gas shows in several Carboniferous reservoir intervals may evidence this petroleum play (geochemical typing evidence is required to prove a Carboniferous, as opposed to Jurassic source). Potential reservoir sand-bodies within the Firth Coal Formation and underlying to laterally equivalent Fell Sandstone Formation (Figure 3) require further mapping but a range of structural trap geometries are possible (Figure 16). Seals could be provided by the overlying Zechstein Group, where evaporite-dominated, or by overlying Mesozoic mudstones.

Together with the petroleum system extent map (Figure 7), these play cartoons illustrate the spatially extensive possibilities of the Devonian and Carboniferous petroleum system elements across the Inner to Outer Moray Firth and northwards to the East Orkney Basin. Recent publications by Reid and Patruno (2015) further extend the Palaeozoic play elements to the median line (Quadrant 16) and northwards to the East Shetland Platform and margins of the Viking Graben (Quadrants 8, 9).

4.2 FIELDS, SHOWS, DISCOVERIES

Studies have shown that Devonian-sourced oils have some key characteristics meaning they can confidently be differentiated from Jurassic-sourced oils (e.g. the presence of carotane and gammacerane; e.g. Bailey et al., 1990). Good quality oil-prone lacustrine source rocks are present in the Devonian both on- and offshore, and are believed to have co-sourced (with Jurassic) the three oil fields in the Inner Moray Firth – Beatrice, Lybster and Jacky (Curran, 1987a; Halliburton Geo Consultants, 1990, Spencer et al., 2014; see Greenhalgh, 2016 for more details). In addition, several oil shows/stains/seeps have been typed to a Devonian source supporting the presence of a mature Devonian lacustrine source rock onshore and in Quadrants 11-13, and possibly into Quadrants 14-15 (Figure 10, 17).

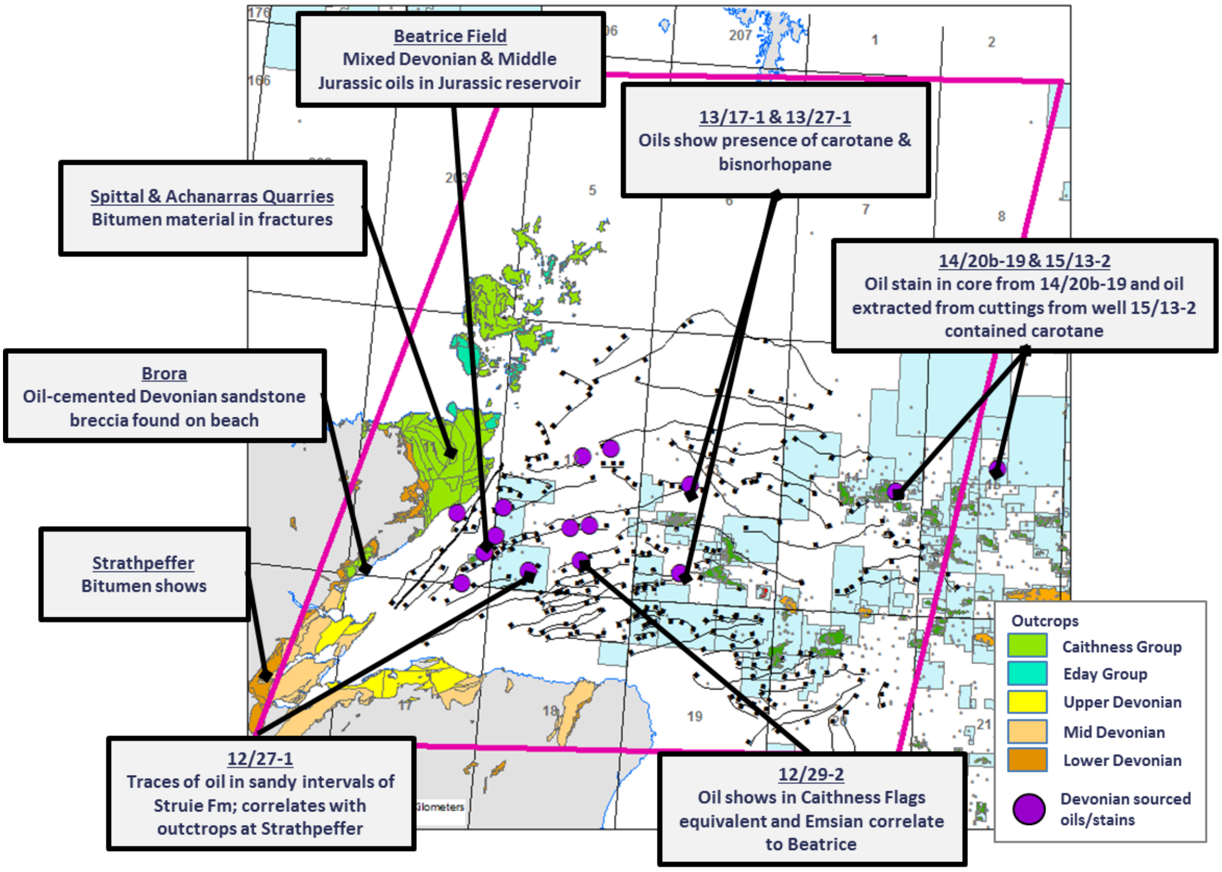


Figure 17 Map showing location of wells with Devonian sourced oils/stains and outcrops. Pink line shows extent of AOI considered in this review. Outcrops from BGS 1:625,000 scale DigiMap©NERC. Distribution of Devonian-sourced oils/stains. Data summarised from Robertson Research International (2001); Peters et al. (1999); Hewett (1993); Marshall (1998); The Geochem Group (1986); Curran (1987a).

The Beatrice, Jacky and Lybster fields (Quadrant 11) produce a high wax crude oil from multi-layered sandstones of the Mid Jurassic (Callovian) Beatrice Formation. The Beatrice Field is located on a tilted Jurassic fault block, the top of which is truncated by the main field boundary fault (Stevens, 1991; Figure 18). The field is overlain by Upper Jurassic mudstone.

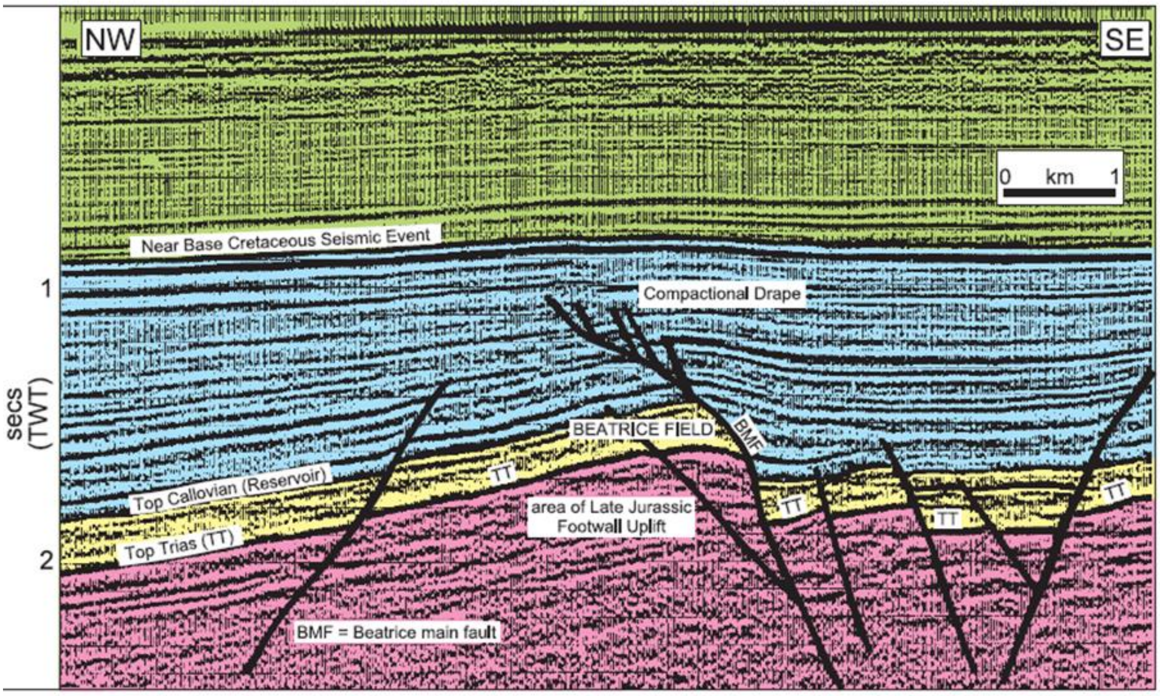


Figure 18 Seismic and structural interpretation of the Beatrice Field, reproduced from Underhill (2003, with permission of The Geological Society, London).

The Stirling Field (blocks 16/21a & b, 16/22) is sourced from the Upper Jurassic Kimmeridge Clay, and utilises a fractured Middle to Upper Devonian braided fluvial sandstone reservoir in a faulted and structural trap. It is sealed by lower Cretaceous mudstone and marl. The superposition of the Stirling and Balmoral fields is an example of the stacked Cenozoic and Palaeozoic play systems (Gambaro and Currie, 2003; Figure 19).

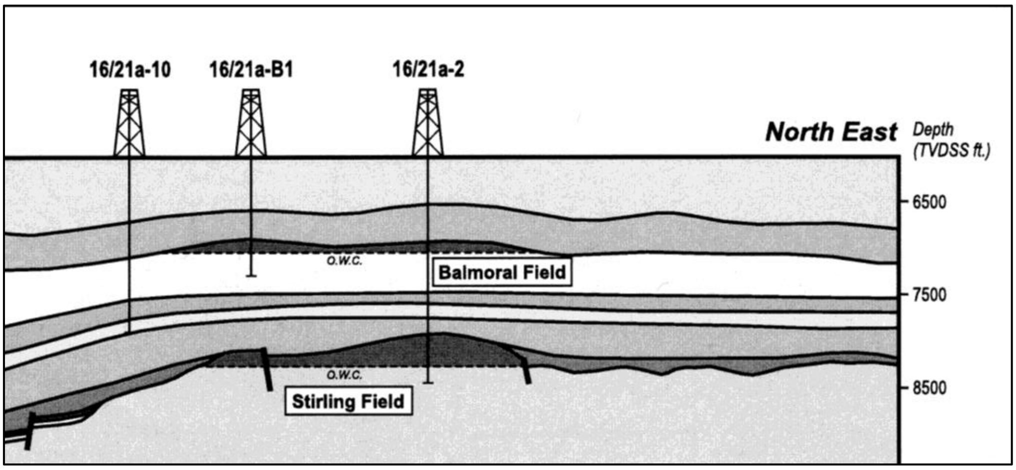


Figure 19 Summary of the Stirling Field and its location underneath the Balmoral Field, from Gambaro and Currie (2003, reproduced with permission of The Geological Society, London). Wells 16/21a- 10 and 16/21a- 2 are approximately 2.1 km apart.

The main producing reservoirs in the Claymore Field are the Jurassic Sgiath Formation and Claymore Sandstone Member (Figure 20) located in a tilted and truncated fault block (Harker et al., 1991). Along with Upper Permian (Zechstein) fractured carbonates, Carboniferous deltaic sandstone forms a secondary reservoir with minor production recorded (Harker et al., 1991). The field is believed to be sourced from the Kimmeridge Clay Formation.

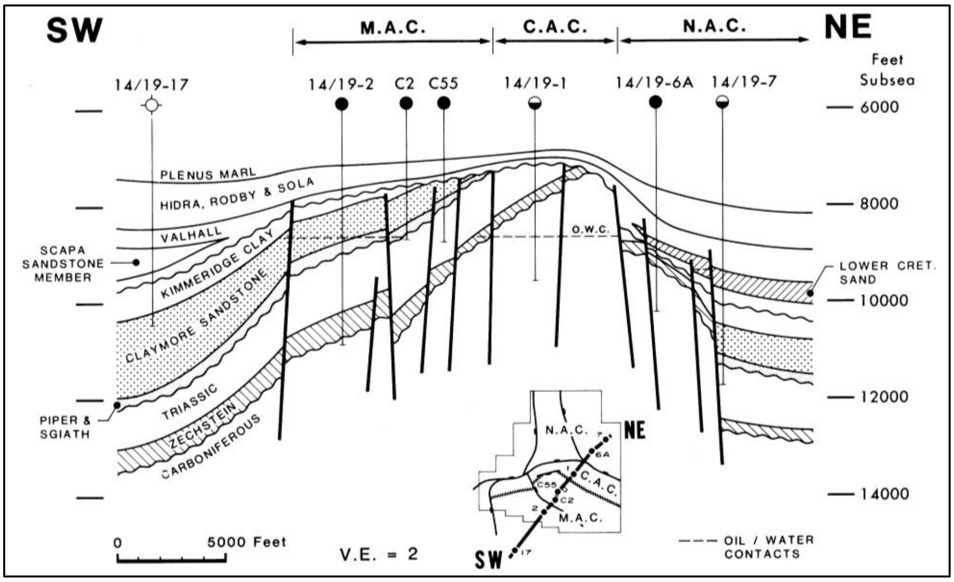


Figure 20 Summary cross-section of the Claymore Field, reproduced from Harker et al. (1991; reproduced with permission of The Geological Society, London).

The Highlander field, also located on the Claymore-Highlander ridge at the margin of the Witch Ground Graben, contains a small crestal, tilted fault block accumulation in a Carboniferous deltaic sandstone (Whitehead and Pinnock, 1991) of the Firth Coal Formation. The source rock is reported as the Upper Jurassic Kimmeridge Clay Formation and the seal is provided by Lower Cretaceous claystone. Interbedded (intraformational) claystone and siltstone are also noted as contributing to the seal of this reservoir (Whitehead and Pinnock, 1991)

Richardson et al. (2005) suggest that oil seeps on the sea surface in the northern part of Quadrant 14 (West Fladen High) are related to reservoir breach through Cenozoic fault reactivation, in an area where a deeply buried Devonian lacustrine source rock is present. They suggest the presence of an active petroleum generating source across the area.

Oil and gas shows are observed within Carboniferous sandstones in Quadrants 14 and 15 (Figure 9), some at multiple levels within the Firth Coal Formation (e.g. 15/19- 2). Glennie (2009) noted that higher sulphur oil is found in major Witch Ground Graben fields (e.g. Piper, Claymore, Tartan, Buchan), and ‘either represents a more sulphur-rich Jurassic facies or a contribution from the Devonian’. Roberston Research International (2001) interpret a possible late to post mature Devonian source kitchen in the vicinity of the Halibut Horst/North Buchan Graben based on gas analysis in block 14/26. Farris et al. (2012) used isotopic analysis to type oil shows in Rotliegend Group sandstone back to non-marine, coal-prone Carboniferous source rocks in well 20/10a- 3.

Given the presence of proven Devonian and possible Carboniferous source rocks in this area, and oil/gas shows within Devonian and Carboniferous strata, the contribution of Palaeozoic-sourced oil and gas to Mesozoic fields should be further investigated. However, no released datasets or publications have been identified during this study to test the contribution of Carboniferous and Devonian sourced hydrocarbon to fields across the wider study area.

4.3 SOURCE ROCKS

4.3.1 Lower-Middle Devonian lacustrine source rocks

The Lower Devonian Struie Formation is interpreted to have a relatively restricted extent in Quadrants 11 and 12 of the Inner Moray Firth, at depths of 2 – 5 km (Figures 21-23, Whitbread and Kearsey, 2016 and references therein).

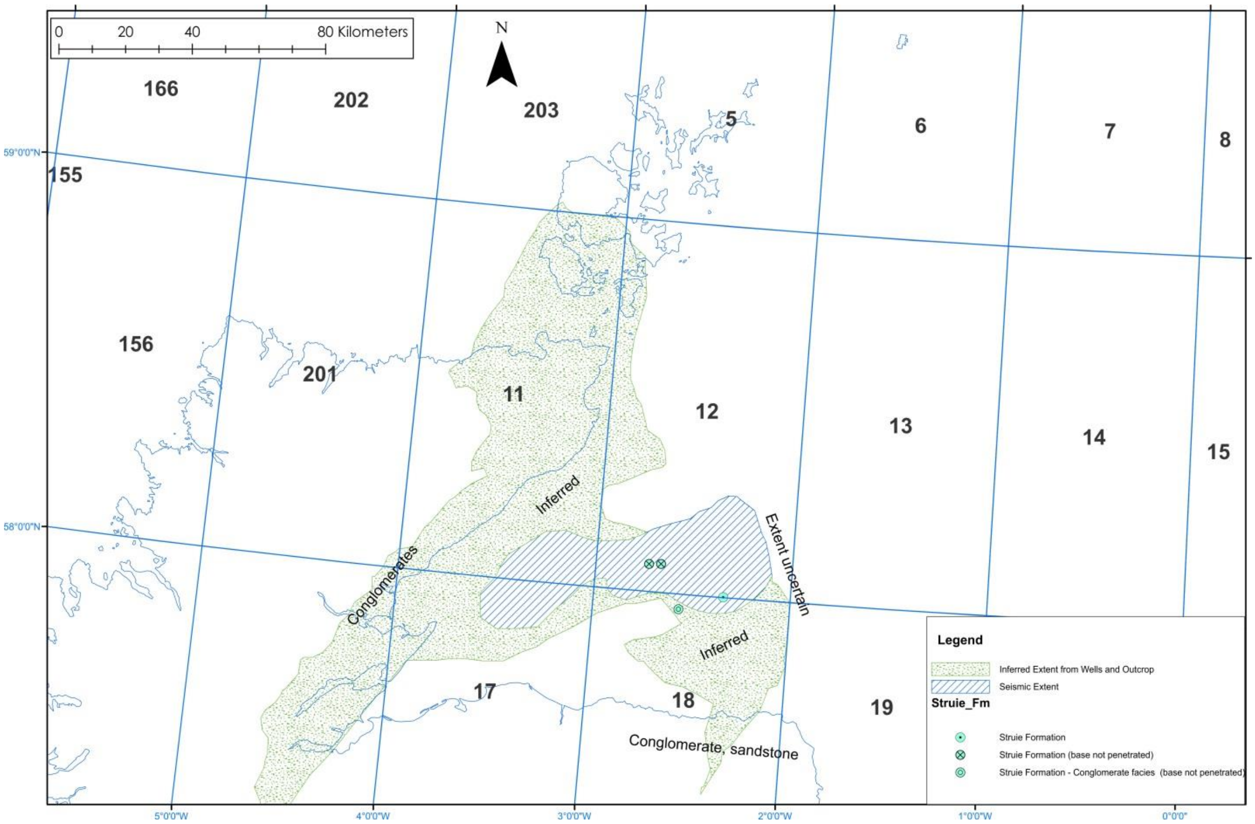


Figure 21 Extent map of the Struie Formation and laterally equivalent conglomerate/sandstone, derived from seismic interpretation, outcrop and well data.

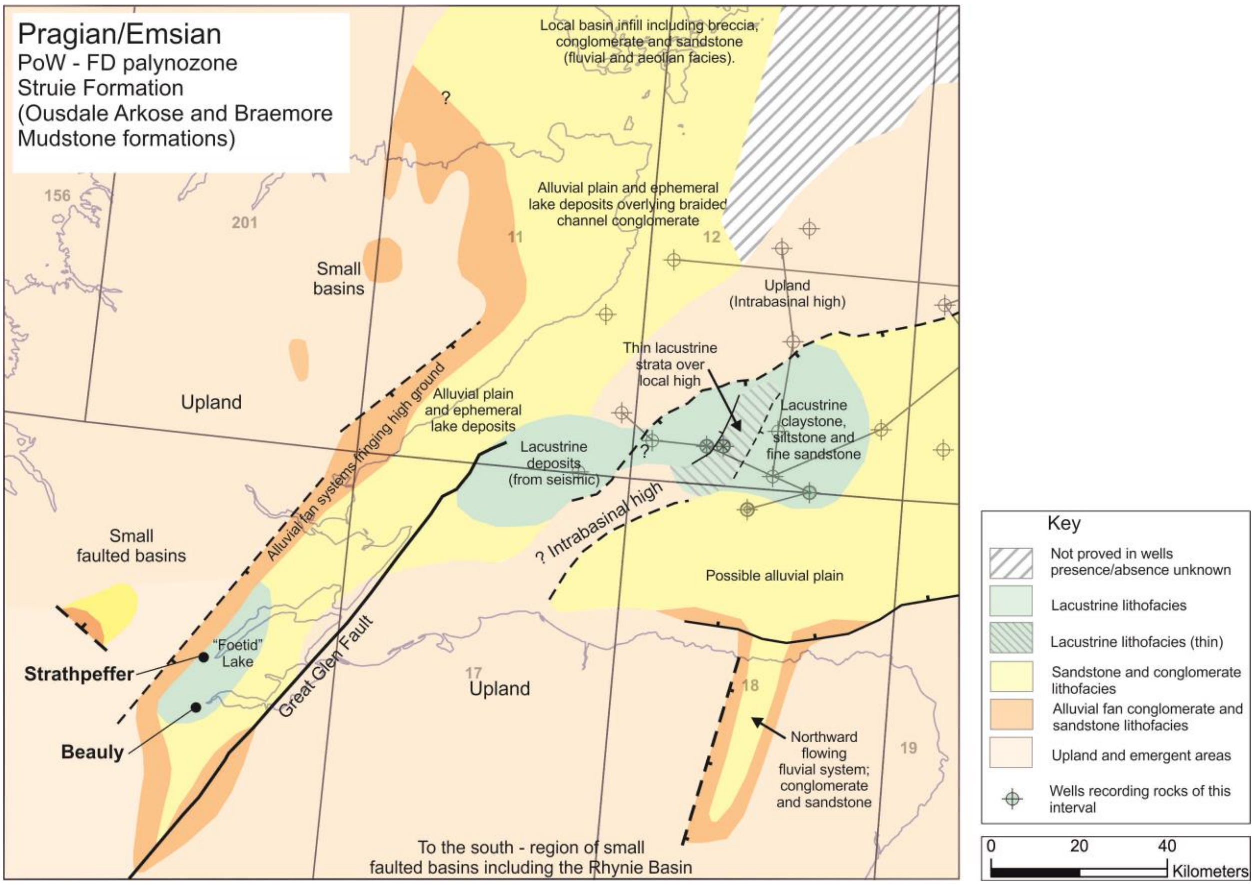


Figure 22 Palaeogeographic reconstruction of the Lower Devonian, Struie Formation interval, from Whitbread and Kearsey (2016).

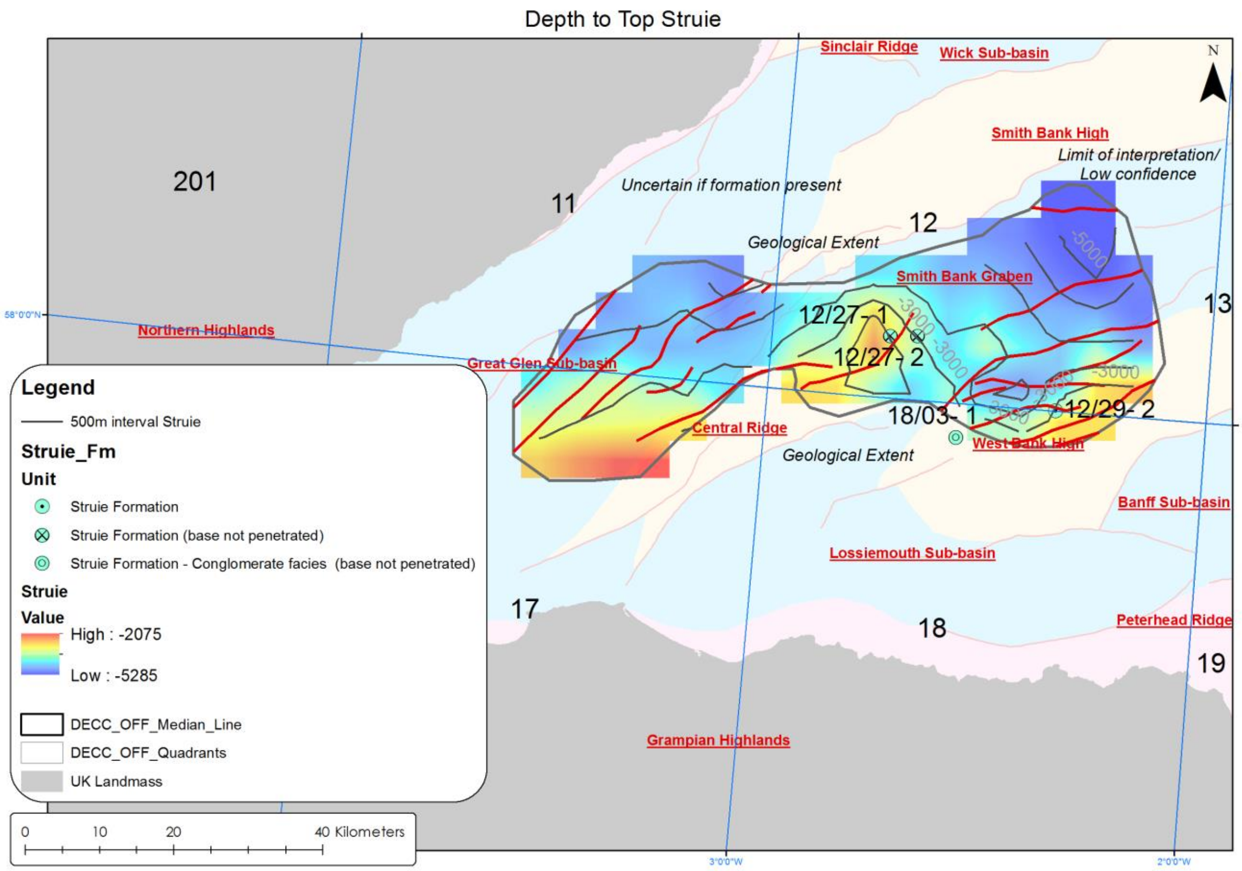


Figure 23. 5 km resolution depth grid to Top Struie Formation (Lower Devonian) in metres below mean sea level from seismic interpretation. The surface represents the lacustrine facies of the formation and not the synchronous conglomeratic deposits as in 18/03-1. From Arsenikos et al. (2016).

The Middle Devonian lacustrine source rock interval is present onshore Caithness and Orkney (Figure 24, Caithness Flagstones), and offshore in the Inner Moray Firth, where it is interpreted in an intercalated mudstone-sandstone interval at the northeastern margin of the Halibut Horst (wells 14/19- 10 and 14/19- 11), and in Quadrant 9 (e.g. 9/16- 3; Duncan & Buxton, 1995; Figures 25, 26). Seismic interpretation for this study (Arsenikos et al., 2016) has mapped the Orcadia Formation to the north of the Halibut Horst, eastwards into Quadrant 14, to depths of over 5 km (Figure 27). In agreement with Richardson et al. (2005) and Reid and Patruno (2015), geochemical typing of migrated oils to Devonian lacustrine source rocks in two samples in Quadrant 14 and 15 (Robertson Research International, 2001), and seismic mapping indicate a more widespread Middle Devonian source rock extent than in the well-documented Inner Moray Firth.

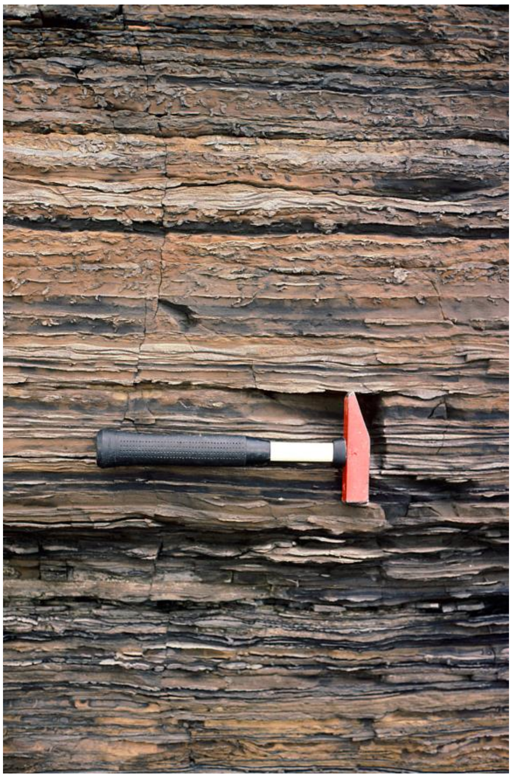


Figure 24 Onshore equivalent of the Orcadia Formation source rock: mudstone-sandstone lacustrine laminites, Lower Caithness Flagstone Group, Old Red Sandstone, Wick Quarries, Caithness. BGS photo P547032 BGS©NERC. All Rights Reserved 2016.

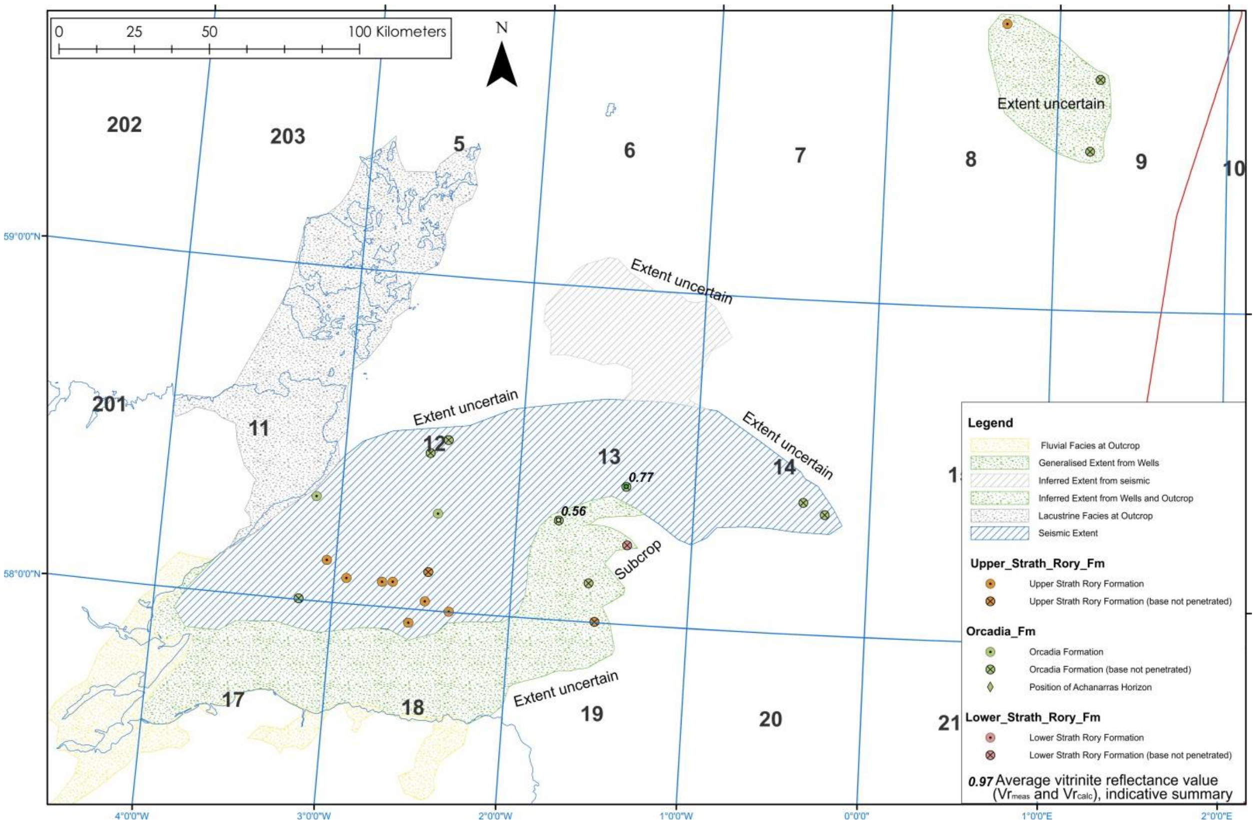


Figure 25 Extent map of the Middle Devonian (source rock interval), Orcadia Formation and laterally equivalent/overlying Upper and Lower Strath Rory formations. Map derived from seismic interpretation, outcrop and well data. Well labels in *black italics* are average maturity (VR) values for the interval.

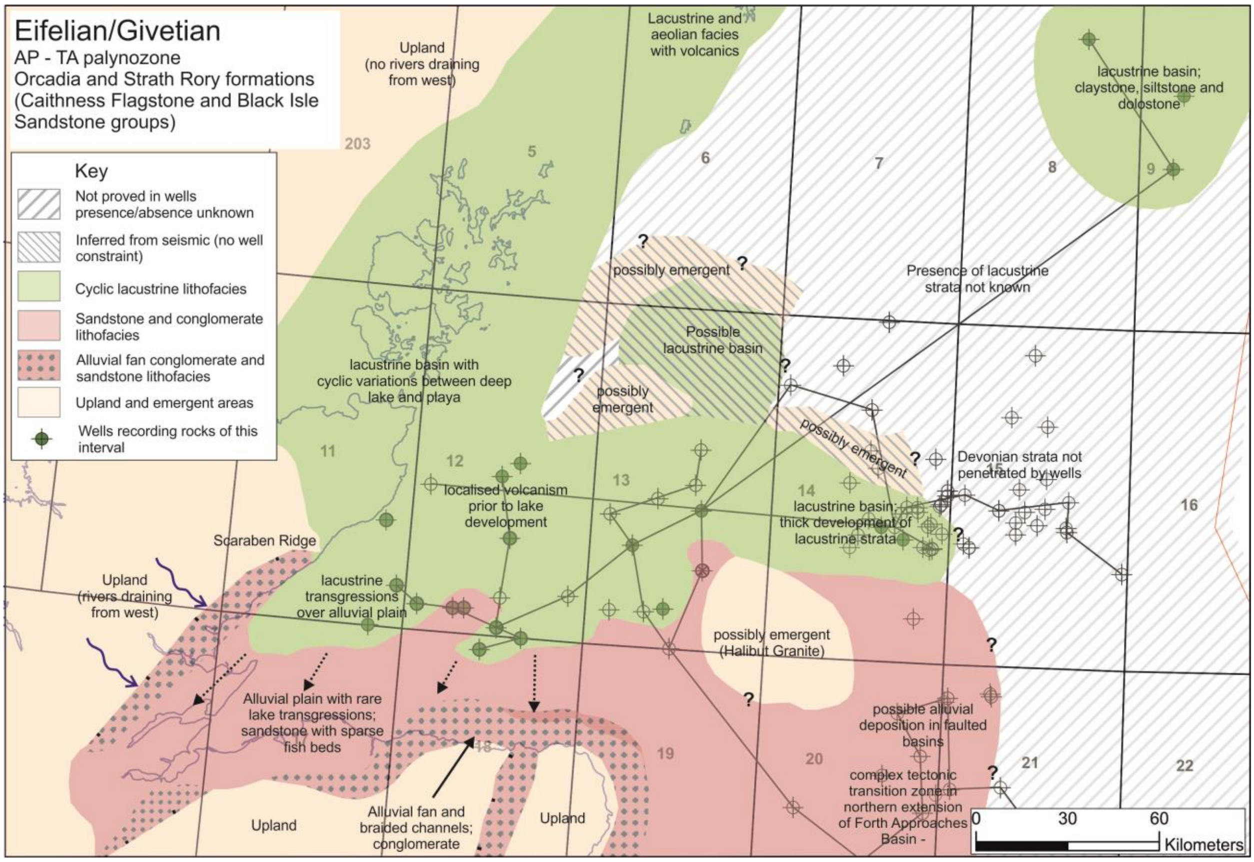


Figure 26 Palaeogeographic reconstruction of the Eifelian to Givetian (Middle Devonian) interval, Orcadia and Strath Rory formations, from Whitbread and Kearsey (2016).

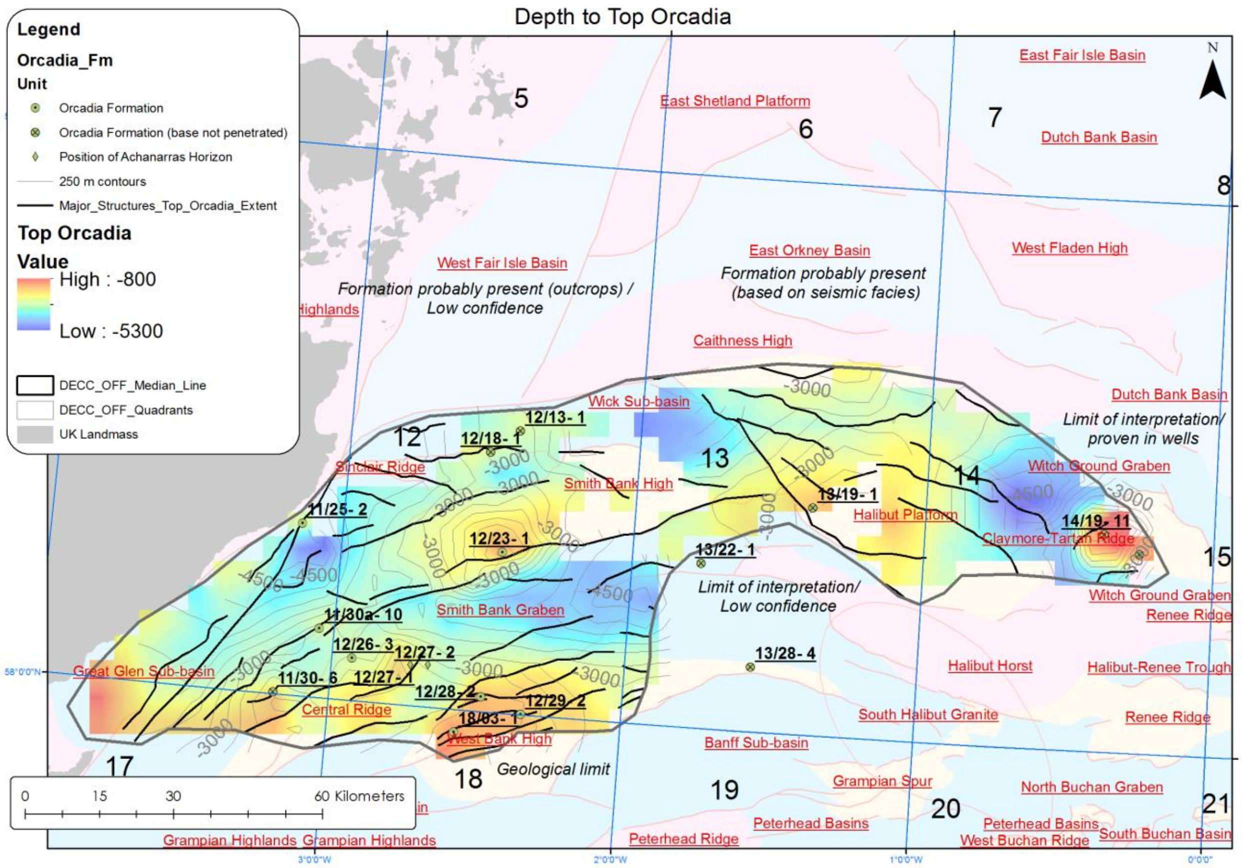


Figure 27. 5 km resolution depth grid to Top Orcadia Formation (Middle Devonian) in metres below mean sea from seismic interpretation (Arsenikos et al., 2016).

The Middle Devonian Eday Group also contains possible source rock intervals e.g. in well 13/22- 1 (Vane et al., 2016). The Eday Group has been seismically mapped to the north and south of the Halibut Horst (Quadrants 13, 20) as well as in the Inner Moray Firth and onshore (Figures 28, 29)

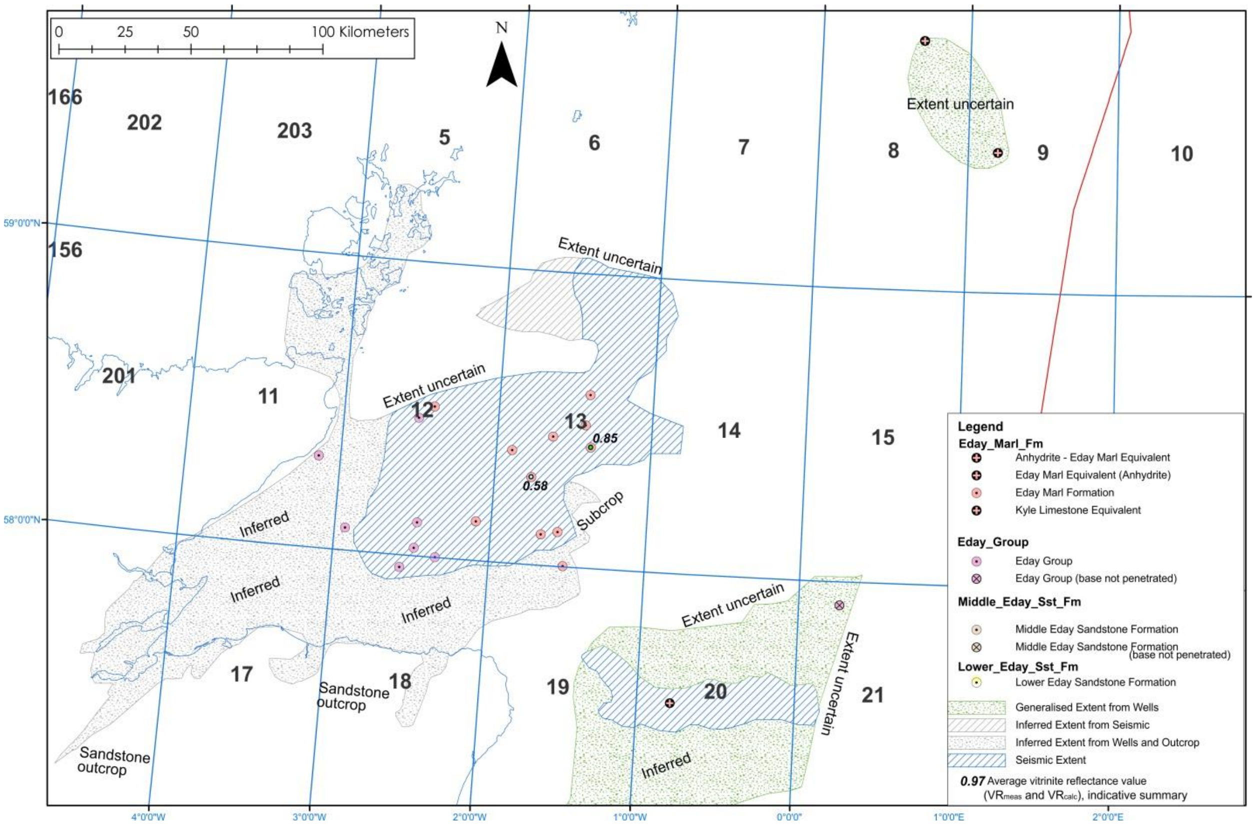


Figure 28 Extent map of the Eday Group (source rock interval, potential local seal, plus some potential reservoir sandstone units) derived from seismic interpretation, outcrop and well data. Well labels in *black italics* are average maturity (VR) values for the interval.

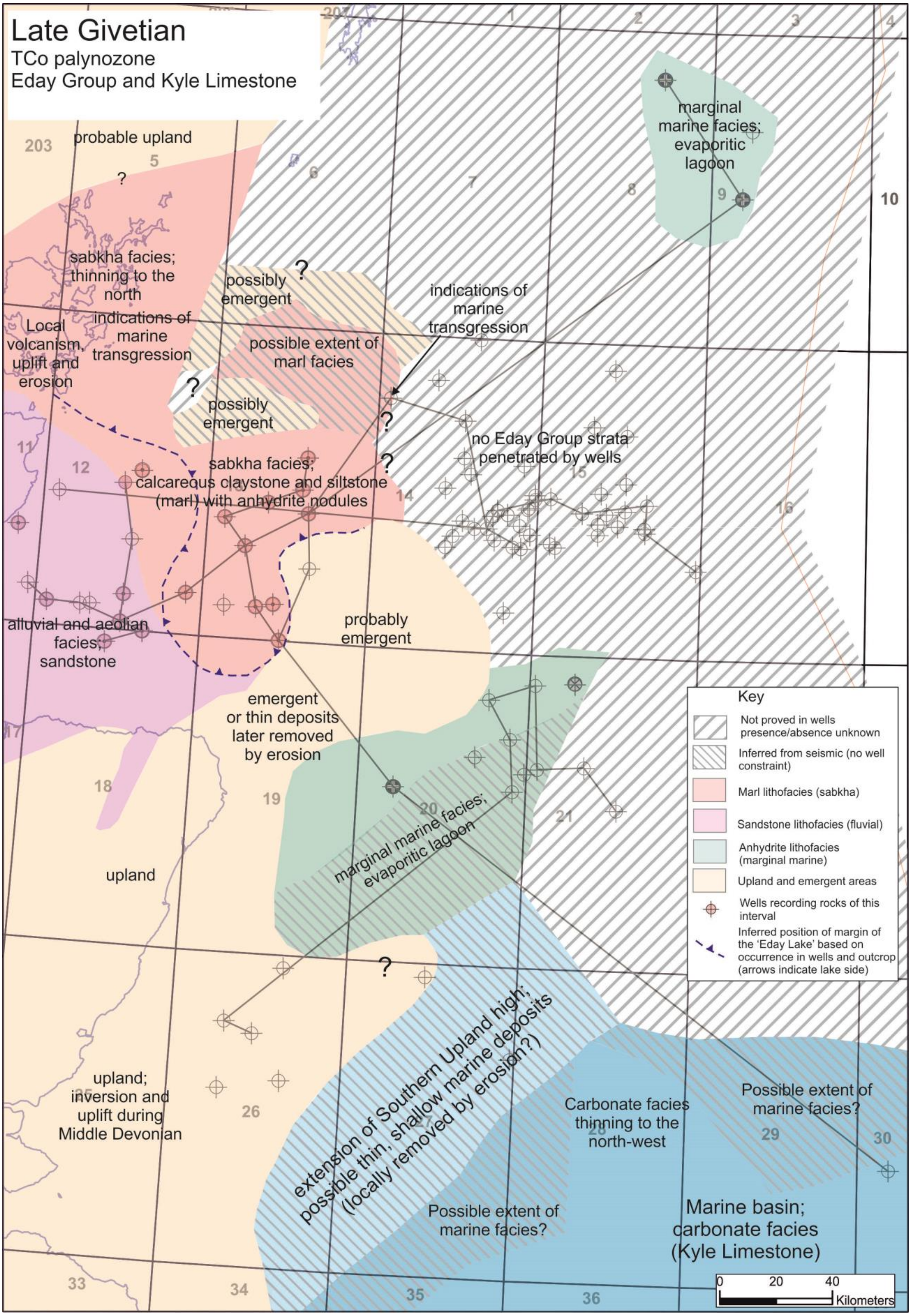


Figure 29 Late Givetian (upper Middle Devonian) palaeogeographic reconstruction for the Eday Group showing links to Kyle Group facies mapped in the Central North Sea (Arsenikos et al., 2015).

The thickness of Devonian source rock intervals varies locally (up to 3.5 km, see Arsenikos et al., 2016) in response to fault-block and basin tectonics combined with uplift and erosion at the Variscan Unconformity.

Published work and commercial reports characterise a good oil-prone source rock potential (e.g. Robertson Research International, 2001; Marshall & Hewett, 2003 & references therein; Figure 30 and see Greenhalgh, 2016 for a summary).

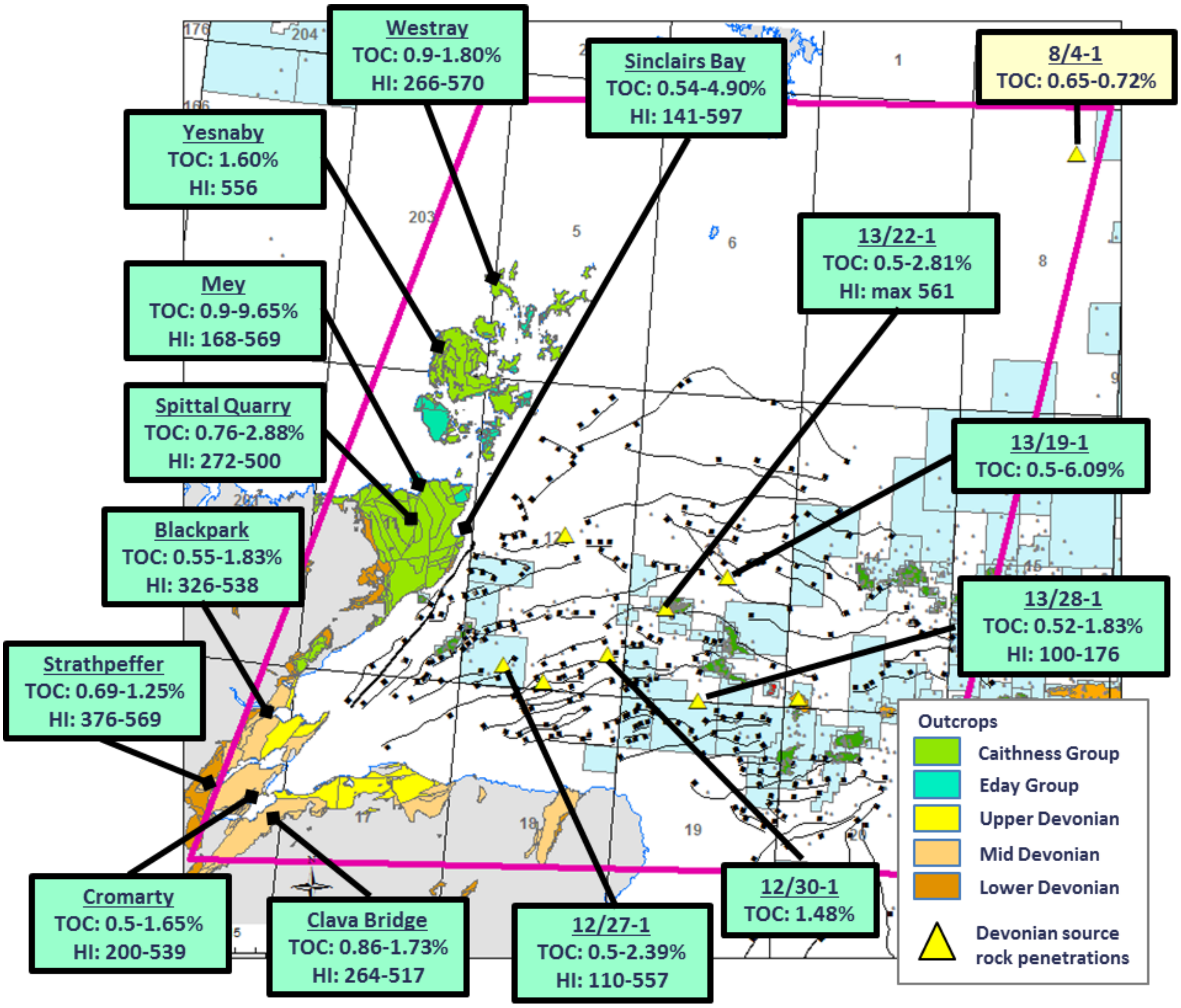


Figure 30 Summary of TOC & HI for Devonian source rock intervals encountered in wells and outcrops. Data from Bailey et al. (1990); Marshall (1998); Marshall & Hewett (2003); Robertson Research International (2001).

Released data compiled for this study (spreadsheet; Vane et al., 2016) illustrates that the Devonian Struie and Orcadia formations and parts of the Eday Group show fair-good oil-prone generative potential in the Inner Moray Firth (wells 12/27- 1, 13/19-1, 13/22-1; Figure 31). Maturity levels are variable, from pre-oil mature to gas mature.

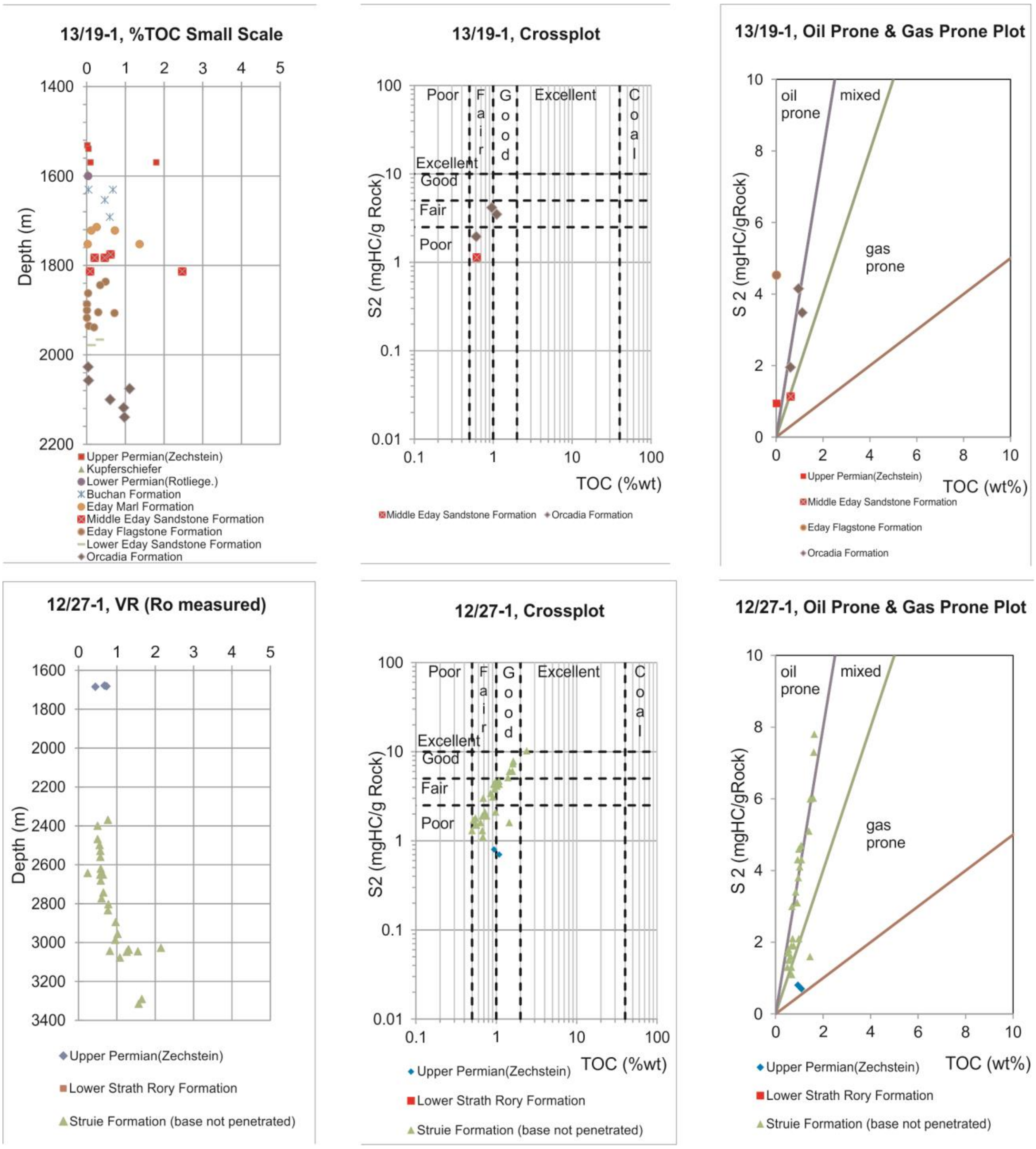


Figure 31 Example of Middle Devonian oil prone source rock quality in well 13/19-1 (above) and Lower Devonian oil prone source rock quality and maturity in well 12/27- 1 (below).

4.3.2 Carboniferous source rock interval

The extent of the Visean-Namurian Firth Coal Formation source/reservoir interval has been defined by well and seismic interpretations (Arsenikos et al, 2016, Whitbread and Kearsey, 2016; Figures 32, 35). Two palaeogeographic diagrams, building on the range of fluvio-deltaic, lacustrine, wetland and marine-influenced environments interpreted by Leeder and Boldy (1990), highlight the depositional environments of the the coal-bearing facies and their equivalent to the Fell Sandstone, Scremerston and Yoredale formations farther south, in and around the Mid North Sea High (Figures 33, 34; Whitbread and Kearsey, 2016).

Only a small amount of released geochemical data is available for four wells in Quadrants 14, 15 that penetrate the Firth Coal Formation. Well 14/30- 1 penetrated a sand-rich interval but the remaining three wells prove poor-excellent quality gas prone source rocks with an oil prone interval, that are at immature to early oil window maturity levels (Figure 10 and Vane et al., 2016). Further detail on the Firth Coal Formation as a source rock is described in section 5.3 below

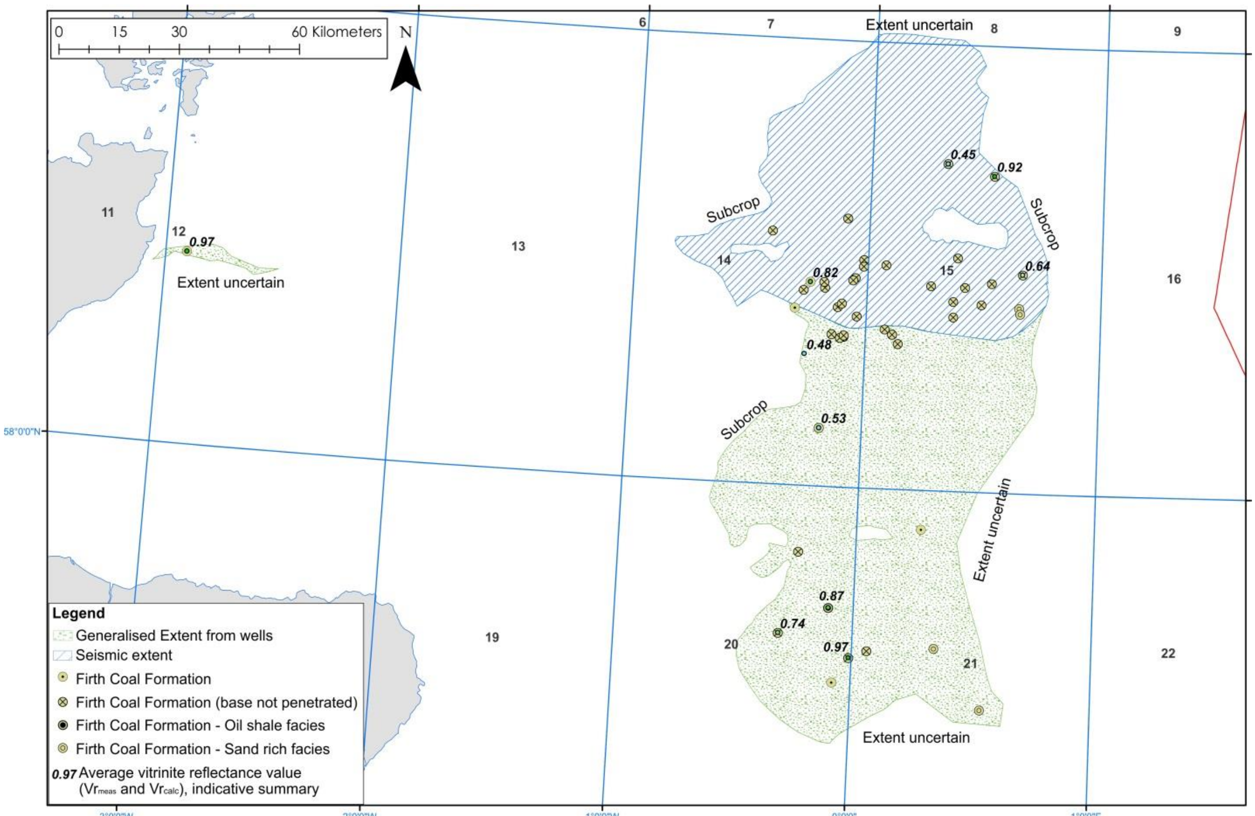


Figure 32 Extent map of the Visean-Namurian (lower-mid) Carboniferous, Firth Coal Formation (source rock interval) derived from seismic interpretation, outcrop and well data. Well labels in *black italics* are average maturity (VR) values for the interval.

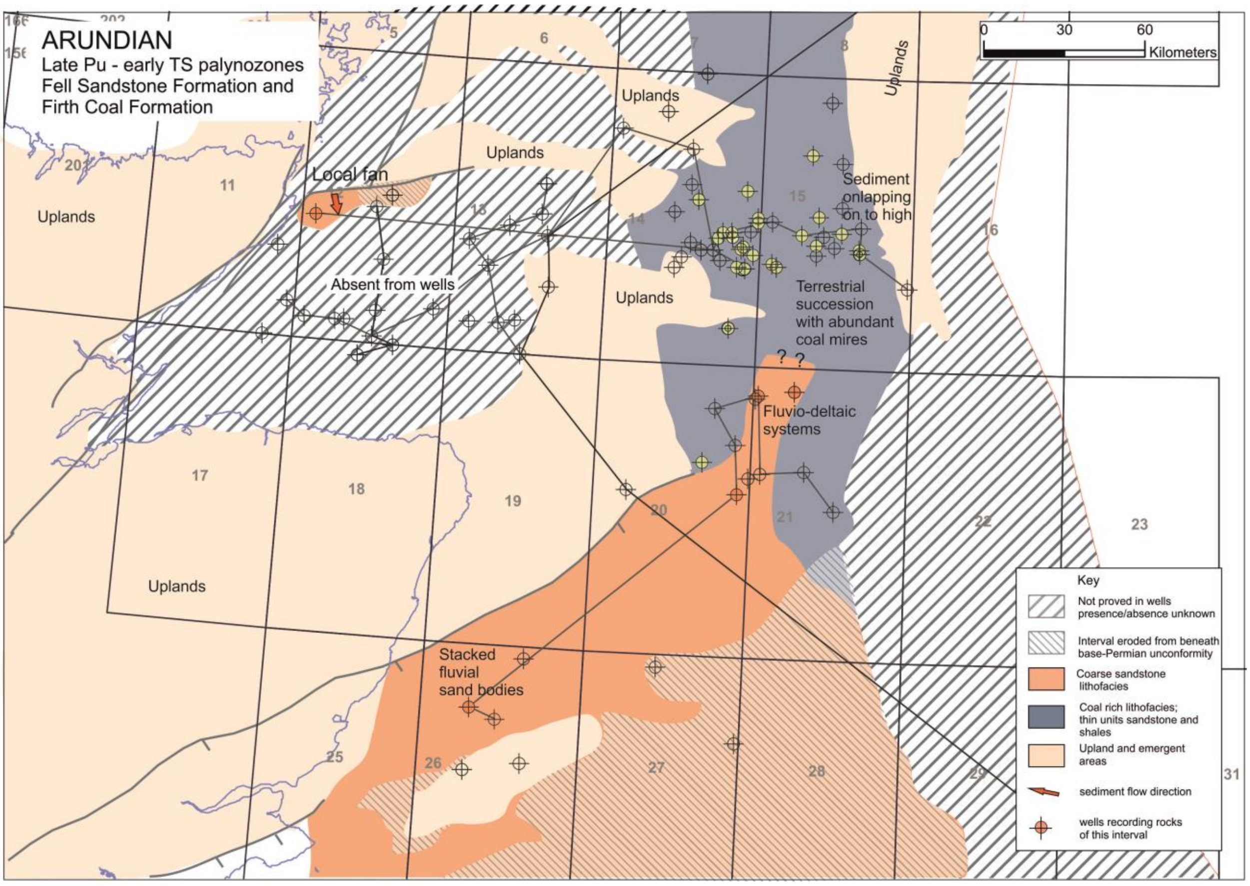


Figure 33 Palaeogeographic reconstruction of Arundian (Lower Carboniferous) times, Firth Coal Formation, from Whitbread and Kearsey (2016).

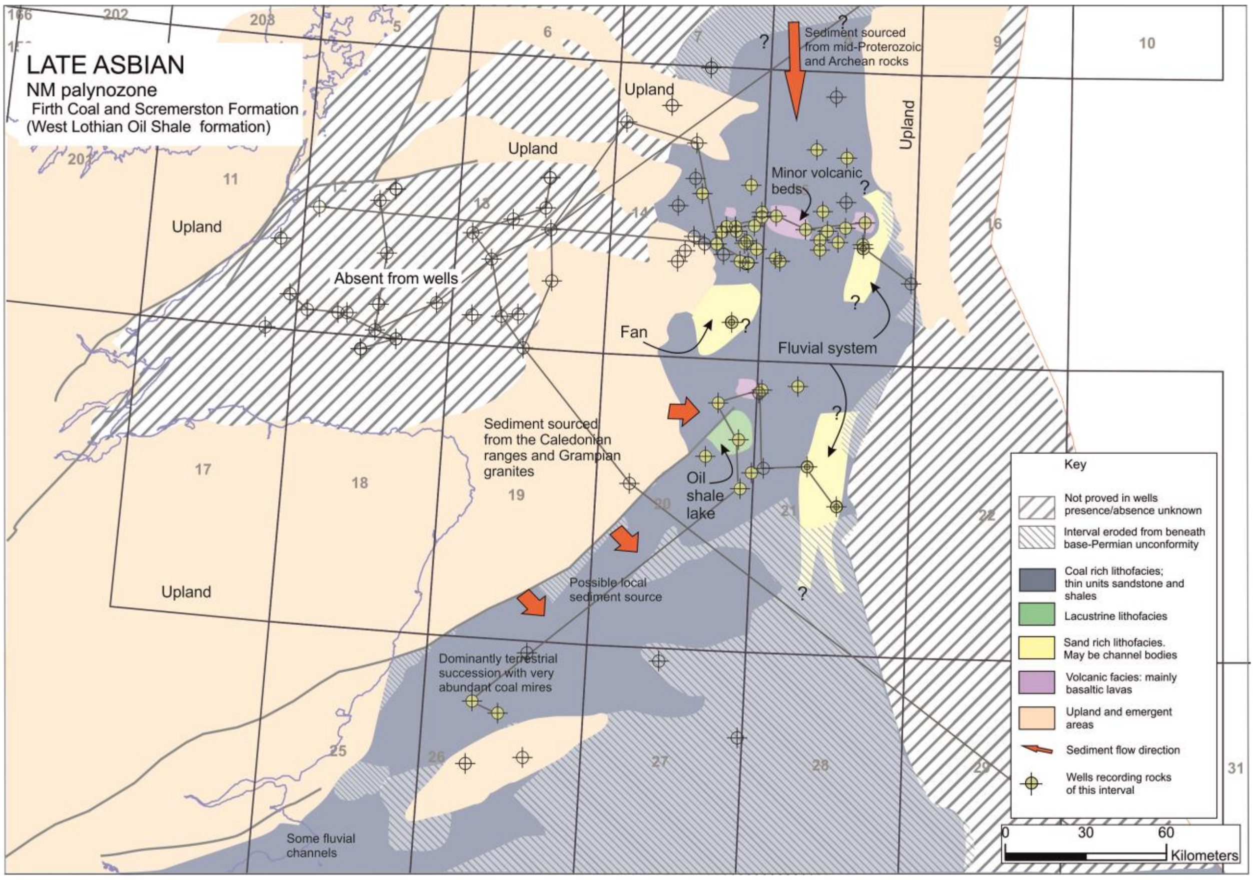


Figure 34 Palaeogeographic reconstruction of Late Asbian (Lower Carboniferous) times, Firth Coal Formation, from Whitbread and Kearsey (2016).

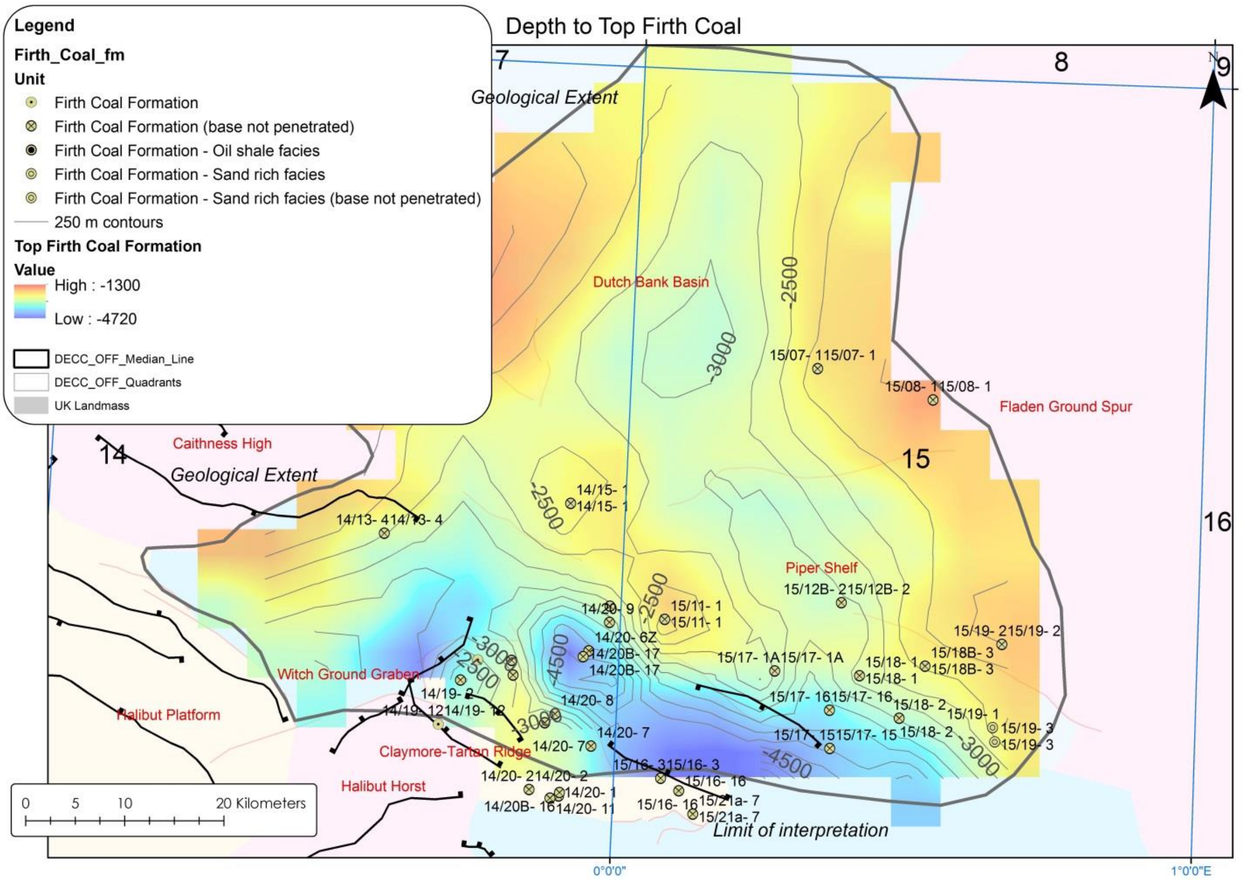


Figure 35. 5km resolution depth grid to Top Firth Coal in metres below mean sea level where seismically mapped in Quadrants 14, 15. From Arsenikos et al. (2016)

4.4 MATURITY, MIGRATION AND CHARGE

4.4.1 Devonian source rocks

Section 2.5 gave an overview of the regional tectonic events and uplft/burial history. Previous work has examined maturity and migration of the Inner Moray Firth in detail. The Devonian is regionally mature to over-mature with the highest maturities observed along the north-east coast of Scotland and in parts of the Orkney Islands, beneath Jurassic depocentres (Curran, 1987b; Robertson Research International, 2001). Onshore, the highest maturities are associated with contact metamorphism by Devonian plutons and area of extremely high maturity is observed along the Great Glen Fault (Hillier & Marshall, 1992). The presence of Middle Devonian volcanics indicates high geothermal gradients in the Devonian (Astin, 1990).

On a local scale, the Devonian source rock is at (present-day) differing levels of maturity in juxtaposed areas due to complex tectonics resulting from post-rift inversion (Robertson Research International, 2001; Hillier & Marshall, 1992; see Marshall and Hewett, 2003 their Figure 6.37).

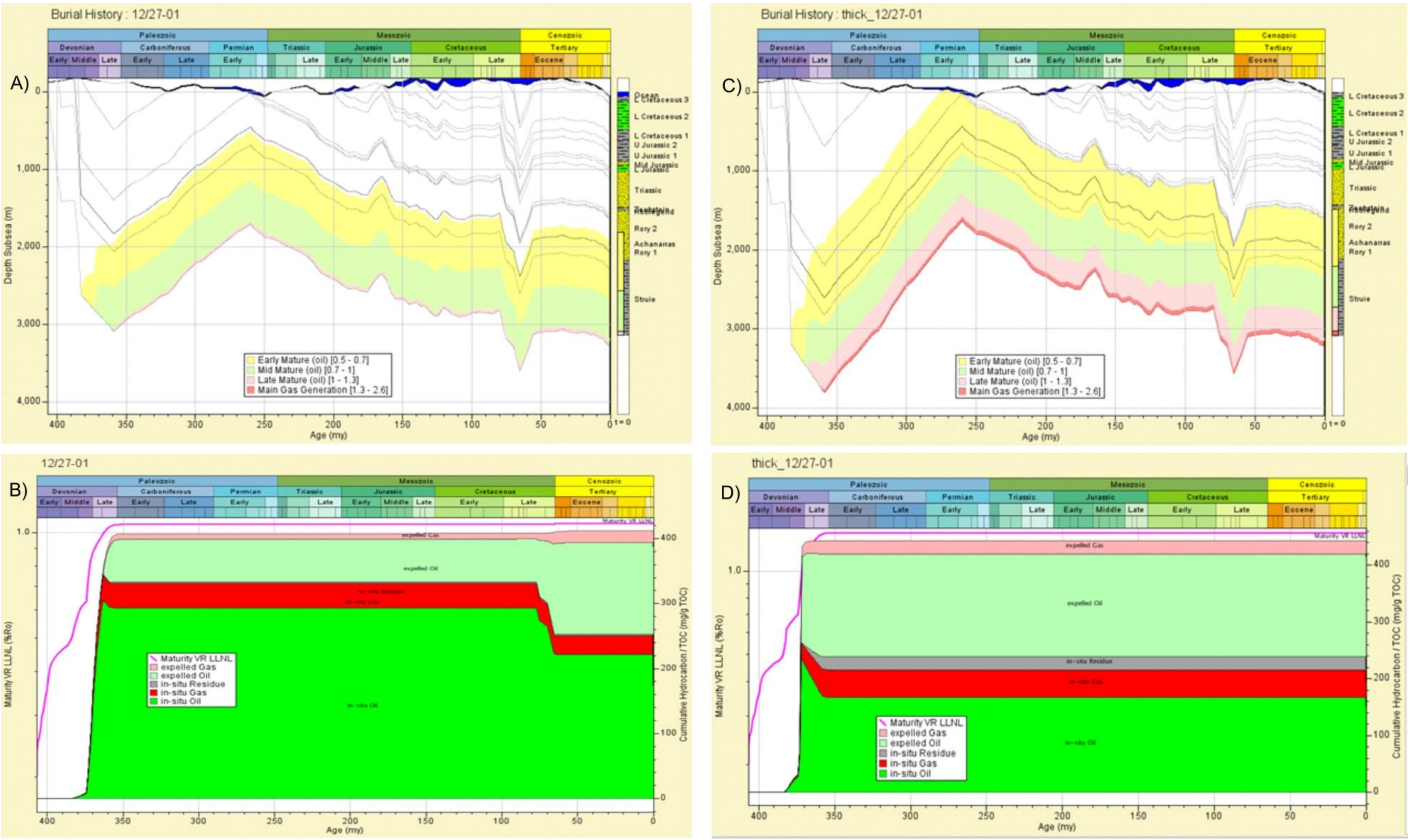
Offshore, high geothermal gradients during Devonian extension may have resulted in early maturation across large areas of the basin (Hillier & Marshall, 1992). The chance of preservation in Devonian reservoirs of any hydrocarbons generated in the Palaeozoic is low due to insufficient seal and deep erosion during the Permian inversion episode (Curran, 1987b; Marshall, 1998). Significant generation from Devonian source rocks during subsequent Mesozoic burial will only have occurred in areas which did not reach late maturity in the Palaeozoic (Hillier & Marshall, 1992). Mesozoic generation is supported by the presence of Devonian-sourced oil in well 12/27-1 (Curran, 1987b).

Long-range migration (over 10's km) is considered limited by significant faulting, high wax-content of Devonian oils and high degree of cementation within interbedded Devonian sandstones by some authors (Hogan et al., 1978).

In the Beatrice Field, Stevens (1991) proposed that the waxy crude migrated over a short vertical path from deeply buried Devonian and Jurassic source rocks east of the main field fault. Maximum burial was predicted during the Mid-Cretaceous with migration occurring prior to the Late Cretaceous (Stevens, 1991). Migration into the Stirling Field was believed to be from the NW and SE, along the major joint and fault patterns within the fractured Devonian reservoir (Gambaro and Currie, 2003)

Patruno and Reid (2015) presented subsidence curves for two wells (14/18-1, 15/6-1) and modelled depths of oil and gas maturation windows, concluding that a Devonian source rock (depths inferred from seismic interpretation) is inferred to have reached peak thermal maturation in the early to mid Cretaceous.

New basin modelling work for this study examined the fate of the Lower Devonian Struie Formation in well 12/27-1. The fault-block nature of the Inner Moray Firth makes it difficult to find a 'typical' well which also had a good spread of constraining maturity data. Well 12/27- 1 is located on a structural high that was a Lower Devonian depocentre but Middle to Upper Devonian relative high and is thus not representative of the wider Devonian succession. Two cases were modelled to accommodate uncertainties in the maturity data (Vincent, 2016) with a significant impact on the timing of generation. If deepest burial was achieved during Devonian times (fitted to higher maturity values, Scenario 2, Figure 36) then main hydrocarbon generation occurred during Devonian burial. However, if deepest burial occurred during Cretaceous – Cenozoic times (best fit to maturity values, Scenario 1) then generation occurred during both Devonian and Cretaceous – Cenozoic times from the Struie Formation (Vincent, 2016; Figure 36).



12/27- 1 Scenario 1 Deepest burial during Cretaceous - Cenozoic times, best fit to maturity values

12/27- 1 Scenario 2 Deepest burial Devonian times, fit to higher maturity values

Figure 36 BasinMod outputs for well 12/27- 1 from Vincent (2016). The well terminates in the Struie Formation and the base of the Struie Formation is not reached. A) Modelled maturity geohistory, Scenario 1. B) Generated hydrocarbons versus time plot showing timing of generation for the bottom of the Struie Formation, Lower Devonian layer, Scenario 1 C) Modelled maturity geohistory, Scenario 2. D) Generated hydrocarbons versus time plot, bottom of Struie Formation model layer, Scenario 2.

Further data collection and 3D basin modelling work on the Devonian source rock interval is recommended, particularly in Quadrants 13 and 14, outside the areas currently highlighted in detailed commercial reports.

4.4.2 Carboniferous Quadrant 14, 15

Carboniferous source rocks in Quadrants 14 and 15 are at immature to early oil maturity levels where sampled from wells drilled on highs (Figure 10, Vane et al., 2016). The presence of oil and gas shows in Carboniferous strata highlights that additional data collection and basin modelling is recommended for future work in this area. Thermal and burial/uplift history modelling of the Carboniferous source rock interval is described for a well in Quadrant 20 (section 5.4).

4.5 RESERVOIR ROCKS

Field and shows described above highlight the involvement of Permian and Jurassic reservoir intervals in hosting Palaeozoic-sourced hydrocarbons. The scope of this study was on the reservoir character of the Devonian and Carboniferous intervals.

4.5.1 Lower - Middle Devonian

There is little existing work on potential reservoirs within the Lower-Middle Devonian clastic successions which occur as lateral equivalents to the lacustrine source rocks (Figure 3, Whitbread and Kearsey, 2016). Core data and petrophysical work was therefore focussed on these intervals (Hannis, 2016).

Core data shows that porosities of up to 20% and permeabilties of up to 100 mD are measured within the Middle Devonian Lower Strath Rory and Middle Eday Sandstone formations (wells in Quadrants 11 and 13, Figure 37).

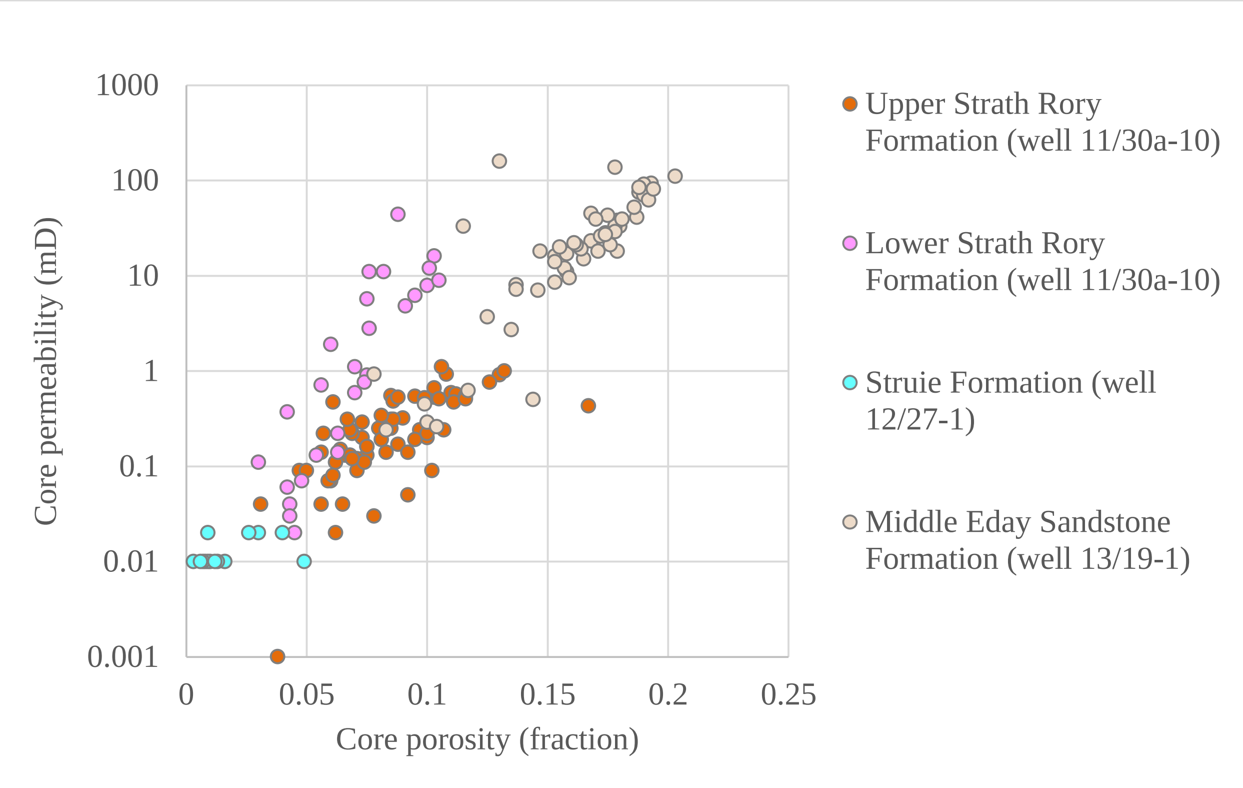


Figure 37 Summary of core porosity and permeability data for Lower-Middle Devonian clastic units in three wells from the Inner Moray Firth.

		Log calculated (for 'net intervals')		Measured on core (from parts of the formation)		Concluding comments
Formation	**Av NTG**	**Highest Av PHI**	**Highest Av PermEst**	**Highest Av PHI**	**Highest Av PermEst**	
Zechstein Group	0.7	0.11	8.15			*Reasonable reservoir potential*
Kupferschiefer	0.13	0.07	0.55			
Rotliegend Group	0.83	0.15	3.15			*Good reservoir potential*
Buchan Formation	0.66	0.12	9.07			
Eday Marl Formation	0.04	0.06	0.35			*Mostly non-reservoir*
Middle Eday Sandstone Formation	1.00	0.14	19.99	*0.16*	*33.62*	*Best net to gross and highest permeability*
Eday Flagstone Formation	0.18	0.09	2.08			
Lower Eday Sandstone Formation	0.15	0.09	3.31			
Upper Strath Rory Formation	0.92	0.16	0.63	*0.08*	*0.30*	*High NTG and porosity, although permeability is low*
Orcadia Formation	0.07	0.07	0.53			*Mostly non-reservoir*
Lower Strath Rory Formation	0.56	0.10	0.68	*0.07*	*5.09*	
Struie Formation	0.01	0.16	1.28	*0.02*	*0.01*	*Lowest net to gross values; not considered to be a reservoir unit*
Granitic basement	0.00	0.05	0.10			

Table 1 Synthesis of core and petrophysical results by formation for three wells (11/30a- 10, 12/27- 1 and 13/19- 1) from the Inner Moray Firth, from Hannis (2016). Porosity (PHI) in percent, permeability in mD.

Petrophysical analysis, matched to core data where available, gives an indication of continuous reservoir quality (Hannis, 2016; Table 1). The best reservoir properties appear to be found in the Middle Eday Sandstone Formation, which, in well 13/19- 1, has a NTG of 1, an average porosity of 14% and an average permeability of 20 mD with values up to 174 mD (estimated from log calculations derived from associated core data). There may also be a potential reservoir in the Upper and Lower Strath Rory Formations, as they have good NTG (0.92 and 0.56 respectively) and average porosities (16% and 10% respectively). However, from the data examined, their permeabilities appear comparatively much lower (averages estimated as less than 1 mD, with the highest values estimated (and measured on core) around 5 mD. Over these potential formations of interest, log responses suggest that there are relatively thick intervals of clean “good” reservoir intervals (Hannis, 2016).

4.5.2 Upper Devonian and Carboniferous reservoir intervals

In the Stirling Field, to the east of the Orcadian study area, a Middle to Upper Devonian reservoir comprises a series of braided fluvial and interbedded sheetflood and overbank deposits, with rapid lateral facies variations within the fluvial depositional environment (Gambaro and Currie, 2003). Oil is produced primarily from fractures and there is a wide range of productivity related to the variable development of the fracture network. An average matrix porosity of 9.5% and average permeability of 0.68 mD can be contrasted with an average horizontal permeability of 4.6 mD in 13.5% of the core interval (Gambaro and Currie, 2003).

In the Claymore Field, Firth Coal Formation sandstones are described as lenticular deltaic sand bodies and are poorly sorted quartz arenites with pervasive ferroan dolomite cement (Harker et al., 1991). Porosity is stated as 19% with variable permabilities up to 0.2 -100 mD (Harker et al., 1991).

In the Highlander Field, the Firth Coal Formation reservoir is described as medium- to coarse-grained, arkosic and poorly sorted (Whitehead and Pinnock, 1991). It commonly fines upwards in sandstone to coal cycles. Individual deltaic sandstone units appear to be of limited lateral extent and may have a ribbon geometry forming discrete sandbodies. Porosity is reduced by kaolinitic cementation and is moderate to low (Whitehead and Pinnock, 1991)

The Upper Devonian Buchan Formation is proven in wells as widespread across the Orcadian study area, with variable thickness commonly exceeding a few hundred metres. It is dominated by sandstone with some pebbly sandstone, conglomerate, claystone and siltstone. The fluvial facies are interpreted as broad sandy braid and alluvial plains, which were locally associated with aeolian dune systems and sabkha environments (Marshall et al., 1996; Trewin and Thirlwall, 2002). Similar facies are observed onshore (Figure 38). Core and petrophysical analysis (Hannis, 2016) examined the Upper Devonian Buchan Formation in the Inner Moray Firth, with favourable properties, particularly in one well (13/19-1) where NTG was 1, porosity 12% and permeabilities estimated as up to 110 mD.

Figure 38 Onshore example of Upper Devonian cross-bedded sandstone (reservoir interval), Dunnet Head Sandstone, Dunnet Bay. BGS photo P219133 BGS©NERC. All Rights Reserved 2016.

Core data from Carboniferous Firth Coal Formation sandstone in Quadrants 14, 15 provides a similar picture to that in the fields described above (section 4.2): a wide variety of porosity and permeability are observed, with low-moderate porosity but commonly low permeability. For example, a sandstone in well 14/13- 4 gave measured porosities between 6.9 – 16.2 % and permeabilities <1 – 12 mD. In well 15/18- 1, measured porosities were between 3.5 – 25.7 % and permeabilities <1 – 109 mD. Further detailed work on reservoir properties, burial depth and reservoir geometries would be beneficial.

4.6 SEAL ROCKS

As the regional Zechstein evaporite seal common in and around the Mid North Sea High is thin and of varying lithofacies (e.g. mudstone with limestone and dolomite, Andrews 1990) or absent, the play cartoons and field descriptions above (section 4.1) highlight the variability of potential seal rocks. Intraformational mudstone seals are possible within the Devonian and Carboniferous successions but lateral continuity and integrity is unknown. Migrated Palaeozoic hydrocarbons in the Beatrice Field are overlain by Jurassic mudstones (Stevens, 1991). In the Stirling field, the top seal is provided by Late Cretaceous marls and chalk (Gambaro and Currie, 2003). Early Cretaceous marls of the Valhall Formation form the seal in the Claymore Field (Harker et al., 1991).

Due to the large variability in possible migration pathways and post-Carboniferous successions, seal rocks should be mapped and evaluated locally.

4.7 TRAPS

Tectonic events such as Devonian and Carboniferous basin formation, Variscan uplift and Jurassic rifting have resulted in a wide variety of potential structural (faulted and folded) and stratigraphic (unconformity) trap geometries interpreted on seismic data at various stratigraphic levels (Figures 14, 15, 16; Arsenikos et al. 2016). Mapping and evaluation at block/prospect scale is required. Published papers on relevant fields and prospects give good local examples (e.g. Edwards, 1991; Harker et al., 1991, Gambaro and Currie, 2003, Reid and Patruno, 2015).

Fault breach is a risk to trap integrity in some areas where faults extend to sea bed (e.g. West Fladen High, Richardson et al., (2005); Inner Moray Firth, Underhill et al., 2001).

4.8 KNOWNS AND RISKS

Palaeozoic petroleum system elements are proven in fields such as Beatrice, Stirling and Claymore. However migration of (i) Palaeozoic-sourced hydrocarbons to post-Carboniferous strata and (ii) migration of Jurassic-sourced oil to Devonian-Carboniferous reservoirs in post-Palaeozoic fault blocks results in complex petroleum plays that require more detailed, local evaluation.

This study has shown that:

- Good quality Devonian and Carboniferous source rocks exist and are spatially more extensive than previously documented. For example, Devonian lacustrine source rocks to the northeast margin of the Halibut Horst, Carboniferous source rocks to the east of the Halibut Horst/Grampian High. However, thickness, extent and quality are likely to be related to a complex fault block topography that is overprinted by younger faulting.
- Further detailed data and work is required on source rock extent, quality and maturity in Quadrants 13, 14, 15 and on typing shows, discoveries and fields. Questions remain as to the potential of Carboniferous oil-prone intervals and possible Palaeozoic-sourced contributions to overlying fields.
- The tectonic history has given rise to significant variations in maturity. The timing of source rock maturation and hydrocarbon migration and timing relative to structural events is critical. For example, any Palaeozoic-age maturation in the Inner Moray Firth would have been too early for Mesozoic to Cenozoic trap formation.
- Further work on basin modelling is required. Devonian and Carboniferous strata buried beneath the Mesozoic – Cenozoic succession in Quadrants 13 – 15 should be prioritised as the limited samples available from wells drilled on highs are at immature to early oil maturity levels, suggesting that the same rocks buried more deeply may be mature, but not overmature/depleted too early.
- Migration pathways are complex due to early and late migration, to a variety of Palaeozoic and younger reservoirs. Seals require detailed, local evaluation.
- High net to gross of Devonian and Carboniferous clastic reservoirs and porosity up to 20% (limited sample set) is promising, but permeability is generally poor and natural fracture permability as in the Buchan field would be required.
- Fault leakage is a risk in the Inner Moray Firth to East Orkney Basin where faults penetrating the Mesozoic succession are close to seabed. This risk decreases in the Outer Moray Firth where faults are sealed by Cenozoic strata.

5 Results: Devonian and Carboniferous petroleum systems of the Grampian High to Forth Approaches

5.1 OVERVIEW

The ‘frontier’ area on the margins of the Grampian High and linking to the northeastern end of the Forth Approaches was highlighted for study by project Sponsors (Quadrants 19 – 21; Figures 1, 39). Seismic mapping of the Devonian-Carboniferous succession from the northeastern Forth Approaches towards the Buchan-Glenn Ridge facilitated linkage with the Mid North Sea High/Central North Sea study area (see Monaghan et al., 2015), though seismic data resolution and limited well ties precluded interpretation over the whole area. The possibilities for pinch-out plays and basement plays were incorporated into the characterisation of petroleum systems at the margins of the Grampian High.

Much of the Grampian High area is interpreted to have been a topographic high during the Devonian and Carboniferous; the succession dips eastwards and is interpreted to onlap the high. It is bounded to the north by the Banff Fault and to south by shallow expression of the Highland Boundary Fault. The WSW-ENE trending Peterhead basins are interpreted to have formed principally during Late Jurassic rifting and significant thicknesses of Jurassic sediments rest on either thin Triassic and Permian, or directly on Devonian or Lower Palaeozoic strata (Figures 39, 40).

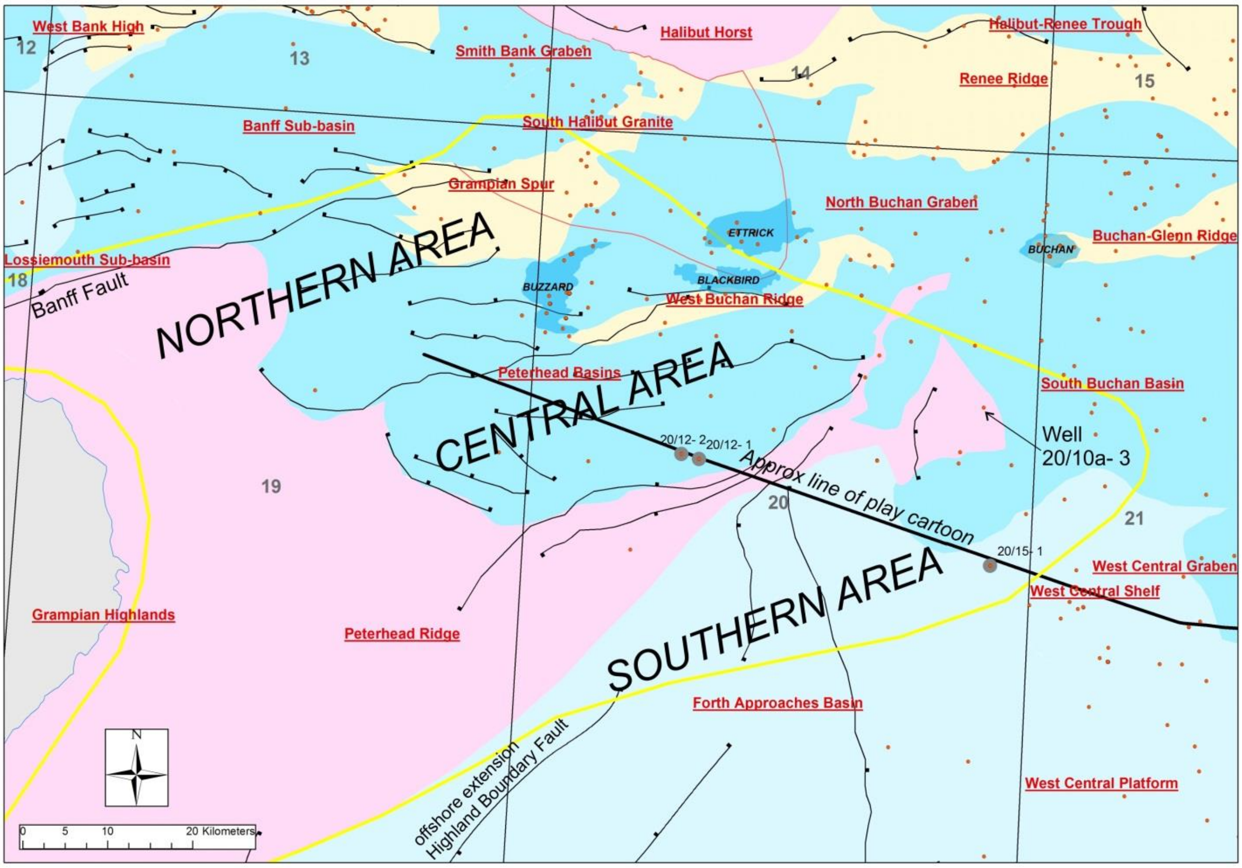


Figure 39 Structural configuration over the Grampian High area (the Grampian High is the area from ‘Peterhead Ridge’ northwards to the Grampian Spur) to Forth Approaches. Yellow polygon shows approximate limit of interpretation from Arsenikos et al. (2016). The location of well 20/10a- 3 used in basin modelling is shown.

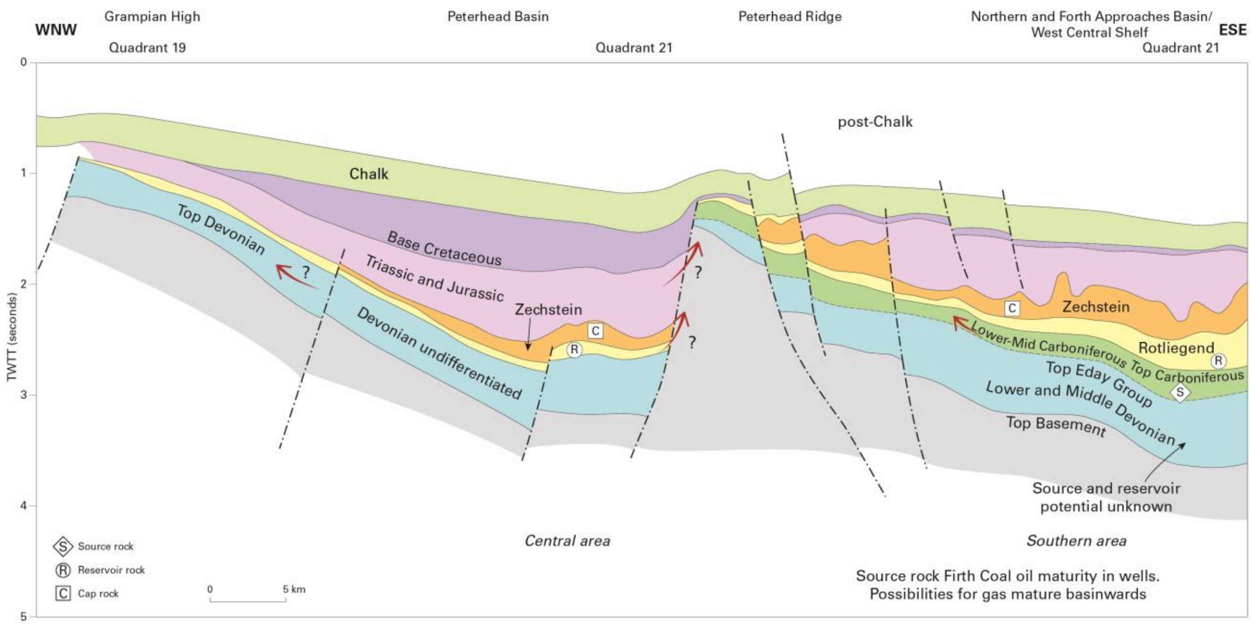


Figure 40 Cartoon of the Grampian High to south Buchan Basin/northeastern Forth Approches petroleum system elements. The red arrows indicate potential hydrocarbon migration pathways. See Figure 39 for approximate line location.

Three conceptual play areas are considered within the wider Grampian high area.

The ‘southern area’ is illustrated on the play cartoon (Figure 40) as a relatively thin (generally less than 1s TWT) Devonian to Carboniferous succession to the south of, and onto the Peterhead Ridge. Source rock intervals are contained within the Carboniferous Firth Coal Formation (Figure 40). Akin to the Forth Approaches area farther south (see Monaghan et al., 2015), a Rotliegend reservoir interval and Zechstein evaporite seal form a Palaeozoic play. In the play cartoon, the high Mesozoic horst block of the Peterhead Ridge offers potential for migration of Palaeozoic and Jurassic hydrocarbons from more deeply buried basins in the east, into possible fractured basement or Devonian-Carboniferous clastic reservoirs. The structural configuration is similar to that at the Buchan Field but in an area where the Jurassic source rock is immature to early mature (Figure 11). Seismic interpretation suggests that potential for a Carboniferous source may diminish towards the south-west, towards a prominent unconformity (Arsenikos et al., 2016).

In the ‘central area’ the potential Devonian-Carboniferous and possible fractured basement reservoirs are situated on faulted blocks such as the Peterhead and West Buchan ridges. Over much of the area the Upper Jurassic Kimmeridge Clay source rock is immature to early mature (Figure 11) but there is potential for Jurassic and Devonian-Carboniferous migrated hydrocarbon, sourced from deep basins to east. The source and reservoir potential of the underlying Devonian Eday Group (proven in one well 21/02- 1) is unknown.

In the ‘northern area’, opportunities exist for a similar configuration of Mesozoic to fractured basement migration as has been illustrated for the ‘Bagpuss’ oil shows in fractured granite/granite wash (Well 13/24a- 2a) adjacent to the Halibut Horst (Jenkins, online). Migration from the north from Banff sub-basin/Smith Bank Graben (Quadrant 13, 19) into the fractured basement reservoir on the Grampian Spur could be possible, or locally within the Peterhead Basins where a potential deep Devonian source may be mature, and Late Jurassic source rock may be early mature.

More detailed seismic mapping and additional well/core analysis is required to better image structural relationships, constrain basin modelling and thus refine the possibilities for the Grampian High area.

5.2 FIELDS, SHOWS, DISCOVERIES

Straddling the boundary between Quadrants 20 and 21 (21/1a and 20/5a), the Buchan Field comprises a fractured Upper Devonian – Carboniferous sandstone reservoir on a Jurassic horst block with four-way dip closure. The top and lateral fault seal is Cretaceous mudstone (Edwards, 1991; Figure 41). A 585 m thick oil column is assumed to result from hydrocarbon migration from mature Upper Jurassic source rock north of the field into the structure, across the bounding faults (Edwards, 1991). The 33.6° API crude oils has comparatively high sulphur, vanadium and extremely high asphaltene content for a North Sea crude, though it is not unduly waxy (Edwards, 1991).

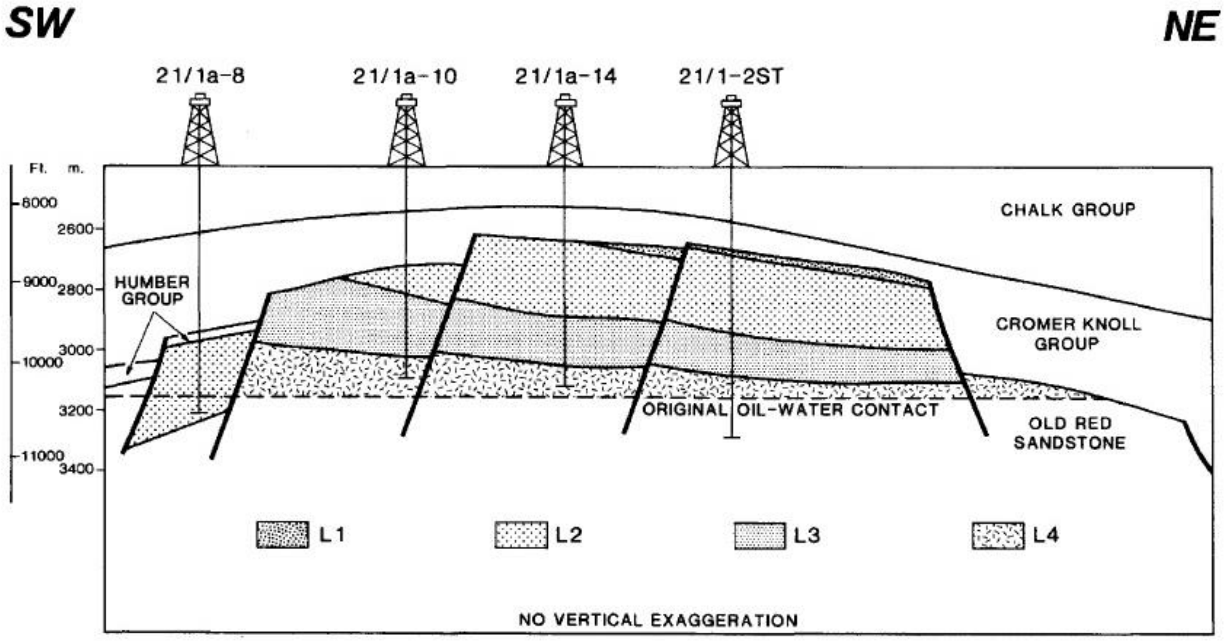


Figure 41 Summary of the Buchan Field from Edwards, (1991; reproduced with permission of The Geological Society, London). Note that units L1, L2 are interpreted as Tayport Formation and L3, L4 as Buchan Formation by Whitbread and Kearsey (2016).

Additionally, a number of oil and gas shows are proven in Carboniferous strata to the east of the Grampian High (Figure 9).

5.3 SOURCE ROCKS

There is a lack of any geochemical data to characterise the possible Devonian source rock of the Eday Group in Quadrants 19 – 21.

The Firth Coal Formation forms the main potential source rock interval, containing numerous coals but also organic-rich mudstones and a thin oil-shale in well 20/10a- 3 (Figure 42). The Firth Coal Formation shows poor-excellent gas-prone generative potential in three wells in Quadrant 20, though maturity levels are variably immature to oil window (Figures 10, 42). The presence of thin oil-shales/oil-prone layers merits further analysis at higher down well resolution (Vane et al., 2016).

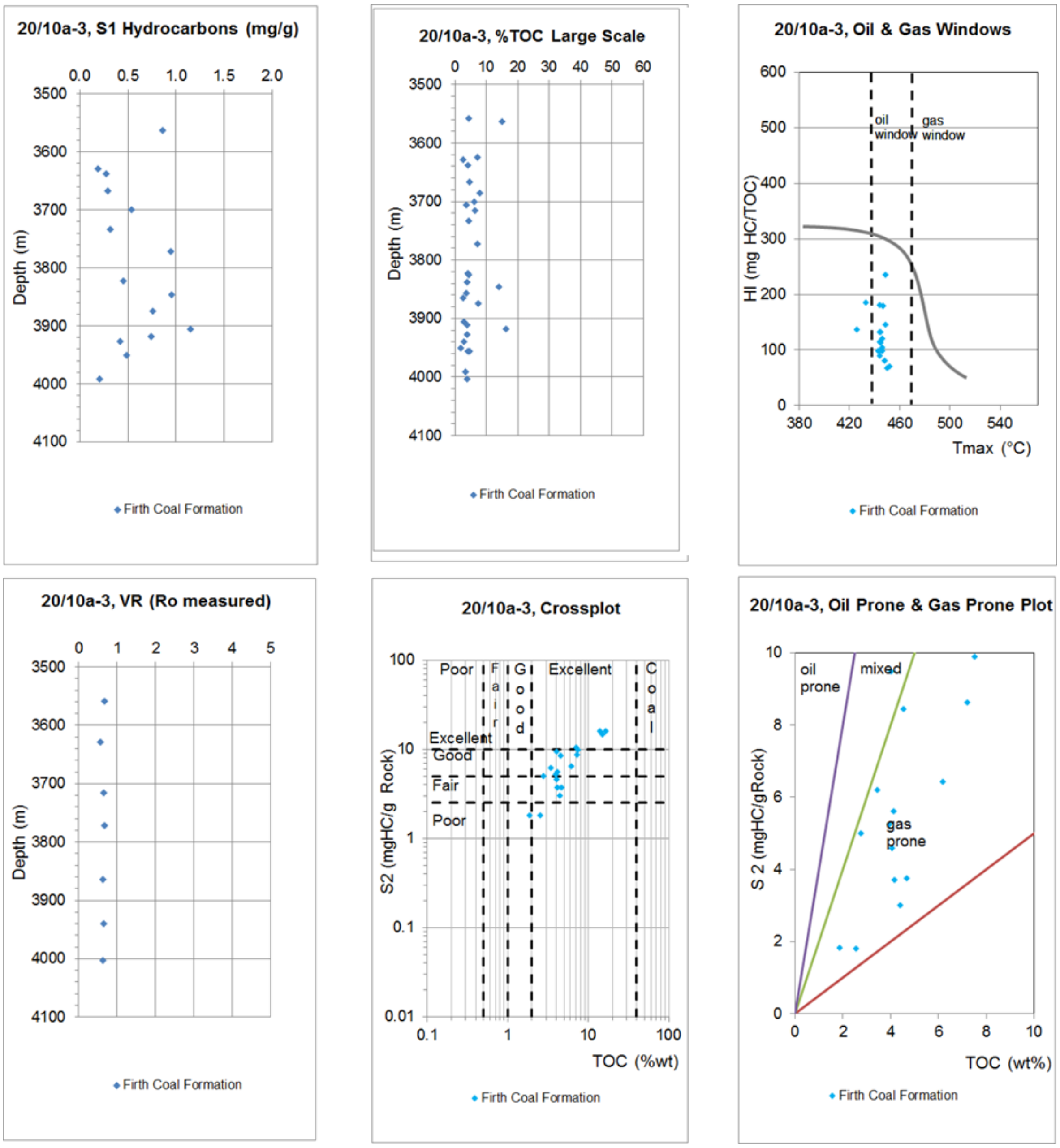


Figure 42 Selection of plots to illustrate source rock quality and maturity in the Firth Coal Formation, well 20/10a- 3. The oil-shale interval is interpreted at 3915 –3921 m.

5.4 MATURITY, MIGRATION AND CHARGE

The Buchan Field provides evidence of migration from Upper Jurassic source rocks, across flanking fault into a horst block with an Upper Devonian–Carboniferous reservoir (Edwards, 1991, see Figure 41). Oil generation is believed to have commenced in the ‘early Tertiary, c.50 ma’ Edwards (1991).

No published or commercial confidential information was located on basin modelling of the Carboniferous succession in this area. Maturity and geochemical sample data to constrain new basin modelling work for this study was limited. Well 20/10a- 3 located at the southern margin of the South Buchan Basin was chosen for 1D modelling because of a spread of maturity data, its apparently representative structural position of a high at a basin margin and of typical facies of the Firth Coal Formation. The model indicates deepest burial and some generation in Cenozoic times, particularly from oil prone intervals in the lower part of the Firth Coal Formation (Figure 43). A ‘scenario’ or ‘pseudo’ well 21/06b- 05 was also modelled in the deeper part of the basin. The depth of the Carboniferous interval was estimated from seismic interpretation. In this well the modelled geohistory suggests Cenozoic gas generation from the Firth Coal Formation (Vincent, 2016).

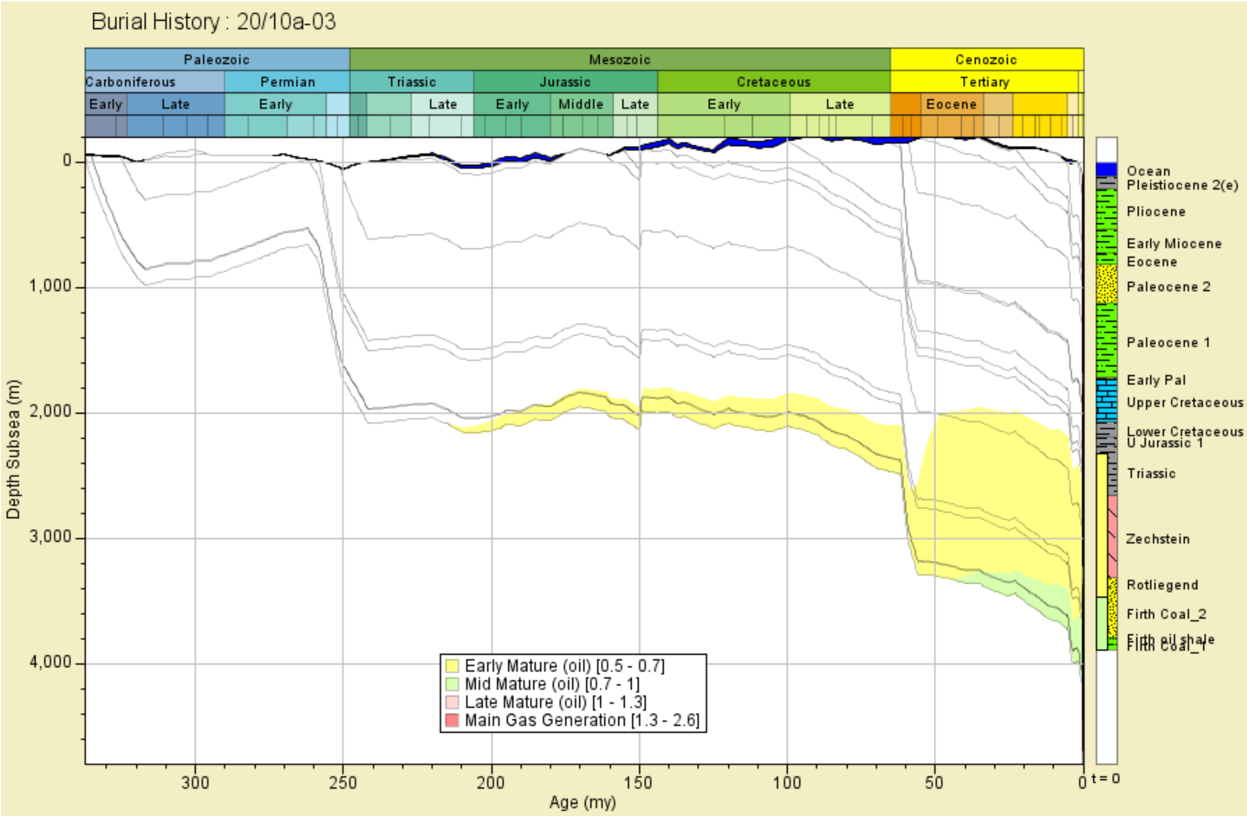


Figure 43 Thermal and burial history curve for well 20/10a- 3 from Vincent (2016).

Though lack of constraining data is a problem, further 3D maturity and migration work is required to further test the hydrocarbon generation and migration pathways from Carboniferous source rocks buried in deeper parts of the Palaeozoic basins, as well as whether the potential volumes of hydrocarbon produced are likely to be economically significant.

The Buzzard Field is believed to be sourced from westwards up-dip migration of Jurassic oil (Doré & Robbins, 2005); a conceptual model can envisage similar, deeper migration pathways from Palaeozoic source rocks, up-dip onto the Grampian High (Figure 40).

5.5 RESERVOIR ROCKS

In the Buchan Field, the Upper Devonian-Early Carboniferous reservoir is described as red, arkosic to subarkosic sandstone with siltstone, mudstone and calcrete pebble conglomerate (Richards, 1985; Edwards, 1991, Table 2). Average matrix porosity is typically 5 – 7% with permeability 0.2 – 20 mD (Edwards, 1991), however a pervasive fracture system increases the average permeability to 38 mD (Bruce and Stemmerik, 2003).

Reservoir subdivision	Net to Gross	Porosity	Reservoir characteristics
L1	0.11 – 0.61 (Average 0.41)	7.7 – 13.9 (Average 9.2)	High sinuosity fluvial facies association with abundant overbank fines, moderate fracture intensity
L2	0.41 – 0.94 (Average 0.71)	6.3 – 10.4 (Average 9.2)	Low sinuosity fluvial facies association, high fracture intensity.
L3	0.85 – 0.99 (Average 0.96)	7.4 – 13.3 (Average 11.7)	Braided fluvial facies association, very low fracture intensity.
L4	0.8 – 0.99 (Average 0.91)	5.5 – 9.9 (Average 7.0)	Braided fluvial facies association. High fracture intensity but highly mineralised.

Table 2 Summary of reservoir characteristics in the Buchan field from Edwards (1991) and Richards (1985). Note that units L1, L2 are interpreted as Tayport Formation and L3, L4 as Buchan Formation by Whitbread and Kearsey (2016).

Well penetrations indicate a widespread extent of the Upper Devonian Buchan Formation over the study area (see section 4.5.2. above). Other potential reservoir intervals include channel bodies within the Firth Coal Formation and the laterally equivalent Fell Sandstone Formation in Quadrants 20, 21.

Limited amounts of core data for the Firth Coal and Fell Sandstone formations shows variable porosity up to 18%, averaging around 10%, and variable permeabilities, in a few cases up to a few hundred millidarcies (Table 3).

	Horizontal Permeability (mD)	Vertical Permeability (mD)	Porosity, %
Firth Coal Fm.	Av. 38 (212 – 0.02) *20/15- 1 Core 1* Av.34.3 (506.0 0.01) *20/15- 2*	Av. 11.5(139.0 – 0.01) *20/15- 2*	Av. 9.8 (1.4-17.0) *20/15- 1 Core 1* Av. 11.7 (18.4 – 2.3) *20/15- 2*
Fell Sst. Fm.	Av. 8 (26 – 0.09) *20/15- 1 Core 1* Av. 67 (266 – 0.02) *20/15- 1 Core 2*	0.2, 0.45 *20/15- 1 Core 1* 38.0 *20/15- 1 Core 2*	Av. 10.1 (16.6 – 3) *20/15- 1 Core 1* Av. 10.6(14.6 – 2.8) *20/15- 1 Core 2*
Tayport Fm.	Av. 1.9 (3.5 – 0.26) *20/15- 1 Core 2* Av. 0.74 (6.1 – 0.01) *20/15- 1 Core 3*	0.03, 0.21 *20/15- 1 Core 3*	Av. 9.5 (13.0 – 5.1) *20/15- 1 Core 2* Av. 9.8 (15.7 – 2.3) *20/15- 1 Core 3*

Table 3 Summary of porosity and permeability from Carboniferous sandstones in wells 20/15- 1 and 20/15- 2. The average is given (Av) followed by the maximum-minimum.

Core porosity and permeability data for selected wells in Quadrants 20/21 is available in the Mid North Sea High/Central North Sea spreadsheet.

The spatial extent of sand-rich facies within the Firth Coal Formation is poorly defined by limited well penetrations that are kilometres apart and not mappable on seismic data. The available evidence suggests they may be interpreted as channel bodies of similar dimensions to those seen onshore and across the southern margin of the Mid North Sea High (Figure 33; Whitbread & Kearsey, 2016)

The Rotliegend sandstones of the Auk Formation form a potentially significant reservoir interval over parts of Quadrants 19, 20 and 21 (Figure 12).

5.6 SEAL ROCKS

In southern parts of Quadrants 20, 21, in the ‘southern area’ a thick Zechstein Group evaporitic succession, strongly affected by halokinesis, likely forms a regional seal. The succession thins and changes lithofacies northwards (Figure 13), such that the seal in the Buchan Field (‘central area’) is provided by Cretaceous mudstones of the Cromer Knoll Group, Valhall Formation (Edwards, 1991). As with the Moray Firth, areas lacking the Zechstein seal are reliant on mudstone seals in the overlying Mesozoic succession, though the character of that succession may change westwards onto the Grampian High. Intraformational Devonian and Carboniferous mudstones seals are possible but are untested.

5.7 TRAPS

Many examples of structural, tilted fault-block configurations offering potential traps at various stratigraphic levels can be interpreted in seismic data (e.g. Figure 40). Large horst block highs such as the Peterhead Ridge, Halibut Horst/Grampian Spur and Buchan-Glenn Ridge form a distinct structural trap type characteristic of this area. The geometry could enable lateral/vertical migration of hydrocarbon into an older reservoir on the horst block e.g. Jurassic oil migrating to an Upper Devonian fractured reservoir in the Buchan Field. Similar geometries and migration pathways can be envisaged for Palaeozoic-sourced hydrocarbon or Jurassic-sourced oil migrating to fractured basement or Palaeozoic reservoirs on numerous similar structural configurations seen across the area (e.g. ‘Bagpuss’ oil shows in fractured granite adjacent to the Halibut Horst).

5.8 KNOWNS AND RISKS

The limited pre-Permian well data and pre-Permian seismic resolution indicate potentially postive Palaeozoic system elements, however the available dataset limits ‘knowns’ for this area.

Knowns include good quality Carboniferous source rocks that are present to the east of the Grampian High. The current wells data indicates largely gas-prone source rocks at oil window thermal maturity levels. Maturity modelling indicates deepest burial at current day, such that the same source rocks buried more deeply in basins adjacent to the sampled wells may account for the observed oil and gas shows.

The Buchan Field is an example of Jurassic oil migrated to a fractured Upper Devonian reservoir in a horst block trap. Similar structural geometries have been observed on and around the Grampian High.

Risks include source rock maturity, long range migration pathways, reservoir quality and presence of seal (particularly onto the Grampian High).

6 Conclusions: knowns and risks for future exploration

6.1 OVERVIEW OF KNOWNS AND RISKS

The descriptions above have highlighted the variation within Devonian, Carboniferous and post-Carboniferous petroleum system elements from the Inner Moray Firth to northeastern Forth Approaches (Orcadian study area). A qualitative ‘traffic light’ summary Table 4 is given below in an attempt to provide a high level summary of the knowns and risks in each age and location *at regional scale*. These summaries are highly generalised and incorporate many variations that require to be further investigated by local studies. The summaries are also highly dependent on the amount and quality of data available. Text *in italics* indicates lack of data and that the assigned colour is low confidence, **bold text** has more supporting data. Black text refers to the Mesozoic component of the petroleum play.

Petroleum system	1. Permian	2 Inner Moray Firth, Devonian – Quadrants 11, 12, 13	3.East Orkney Basin, Dutch Bank Basin Devonian – Quadrants 6-8, northern 12-15	4.Witch Ground Graben to Buchan Basin, NE Forth Approaches, Carboniferous and Devonian (Quadrants 14, 15, 20, 21)	5.Grampian High – Devonian to lower Carboniferous (Quadrants 19, 20)
Source	*Minor sources within Zechstein* **(Sources are Jurassic or Devonian/Carboniferous)**	**Proven oil source in Devonian lacustrine mudstones, geochemically typed onshore and offshore (e.g. Beatrice). Extent and quality may be variable** (Jurassic, Kimmeridge Clay immature/early mature or absent)	*Devonian Source rock interval proven in small number of wells e.g 13/19- 1,14/19-10* *Intervals mapped on seismic at variable depths but lacking well penetrations.Source quality unclear.* (Jurassic, Kimmeridge Clay immature/early mature or absent)	**Good quality Carboniferous source, largely gas prone, ?oil prone intervals. Immature to oil-window maturity in samples from highs. Detailed extent/quality requires further data** **(Jurassic, Kimmeridge Clay early mature to mature)**	*Possible source rocks within Devonian and lower Carboniferous, lack of data* *(Kimmeridge Clay immature to absent on parts of the Grampian High)*
Reservoir	**Rotliegend (Auk) reservoir in south Quadrant 20-21** **Zechstein vuggy carbonate reservoir in Carnoustie Field** *Reservoir quality, presence and thickness in northern Quadrant 20-21 and Quadrant 11-16 variable*	*Potential reservoir intervals Middle and Upper Devonian, require natural fracturing to increase permeability* **(Jurassic reservoir in Beatrice Field)**	*Lacking well penetrations/core data. Potential reservoir intervals Middle and Upper Devonian likely to require natural fracturing to increase permeability* *(Mesozoic reservoirs possible, where present)*	**Proven Upper Devonian-Lower Carboniferous clastic reservoirs in Buchan, Claymore, Highlander, Stirling. Permeability enhanced by natural fracturing** *Extent of sand bodies unknown* **(Many Mesozoic fields/reservoirs, Permian reservoir also proven)**	*Potential reservoir intervals Middle and Upper Devonian, likely require natural fracturing to increase permeability*
Seal	**Zechstein evaporites in south Quadrant 20, 21.** **Zechstein faulted, thin or carbonate rich over much of Quadrants 13- 15, 19** **Zechstein absent or clastic facies in Quadrants 11-12**	*Intraformational Devonian seals possible, not tested?* **(Mesozoic seal in Beatrice Field)**	*Intraformational Devonian seals possible, not tested* *(Permian and Mesozoic seals possible, where present)*	*Intra-Carboniferous mudstone seals possible, not tested* **(Mesozoic seals e.g Cretaceous mudstones in Buchan Field)**	*Intraformational Devonian seals possible, not tested* *(Permian and Mesozoic seals possible. though facies likely change onto the Grampian High)*
Traps	*Potential structural and stratigraphic trap geometries at Base Permian Unconformity, particularly in southern Quadrants 20-21*	**Numerous opportunities for potential structural and stratigraphic traps** *Faults penetrating close to seabed pose risk of leakage*	**Numerous opportunities for potential structural and stratigraphic traps** *Faults penetrating close to seabed pose risk of leakage (seep survey)*	**Numerous opportunities for potential structural and stratigraphic traps**	*Opportunities for structural and stratigraphic trap geometries (e.g. horst block closures) require local evaluation of seal*
Maturity, migration	*Dependent on location, source type, trap etc requires local evaluation*	**Devonian variably oil to gas window mature. Mesozoic-Cenozoic generation modelled. Migration to Mesozoic reservoir/trap in Beatrice Field.** *Risk of Palaeozoic maturation/depletion and Mesozoic breach. Locally immature in east.*	*Lack of well penetrations and data. Current day burial depths in East Orkney Basin and other basins comparable to Inner Moray Firth. Other areas Devonian at shallow depths*	*Carboniferous source rock maturity/maturation requires further testing into basins. Modelled as gas mature in basin centre* **Migration of Jurassic oil to Upper Devonian-Carboniferous reservoir successful play in Buchan, Stirling, Claymore**	*Potential for up-dip migration of Carboniferous, possibly Devonian, or Jurassic sourced hydrocarbon into Palaeozoic or younger reservoirs. Further study required*

Table 4 Qualitative indication of knowns and risks for conventional petroleum exploration plays using a traffic light colour scheme at regional scale in Palaeozoic petroleum elements of the Orcadian study area. Relevant post-Palaeozoic elements are shown in black. At block/prospect level risks are much more complex and dependent on local geology. Text *in italics* **indicates lack of data and lower confidence than bold text. The spatial and temporal extent of the columns are indicated in Figure 44.**

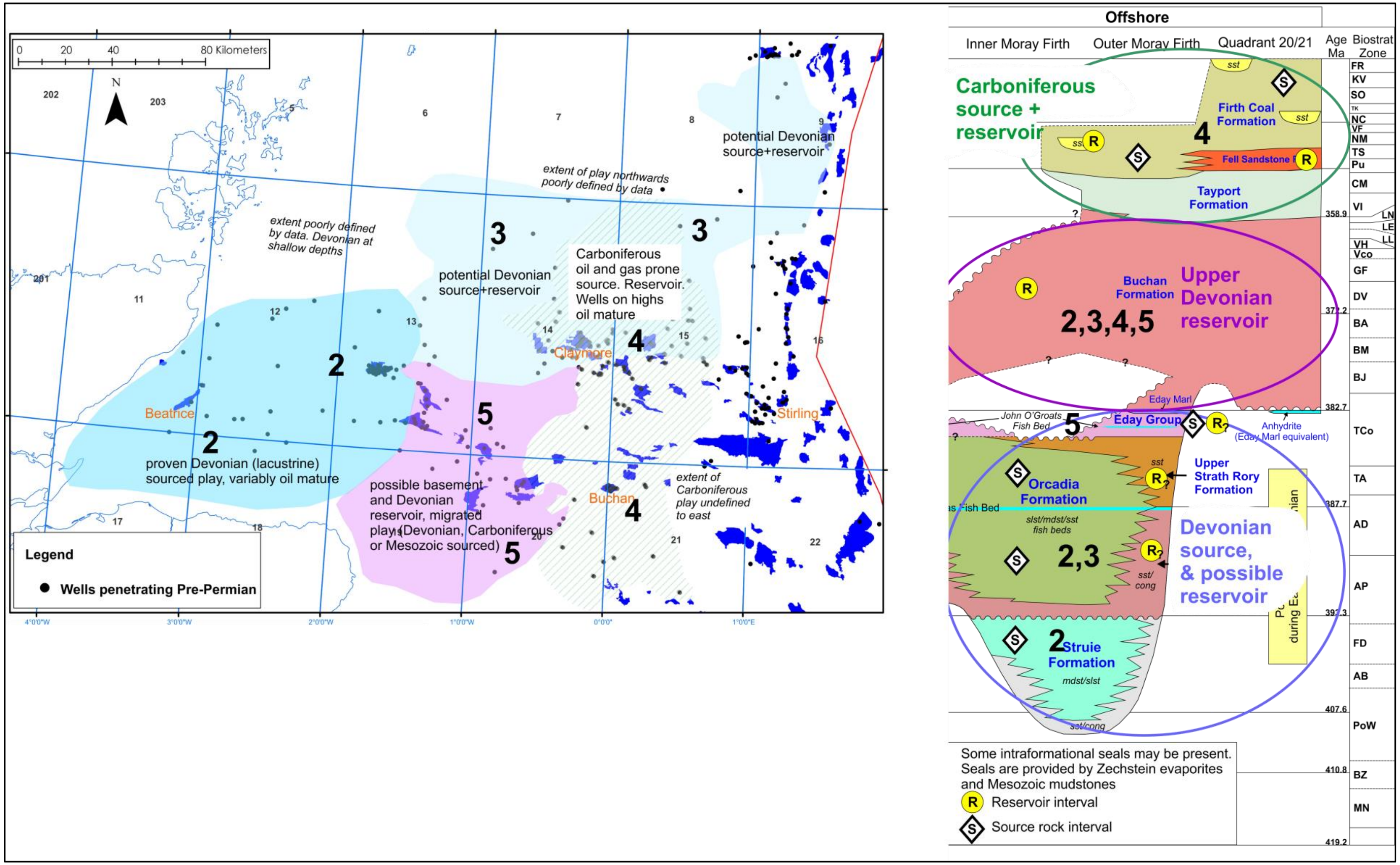


Figure 44 Indication of the spatial and temporal extent of petroleum systems described in the columns in Table 4 above. Note that where numbers are missing from the map the play type covers the majority of the area.

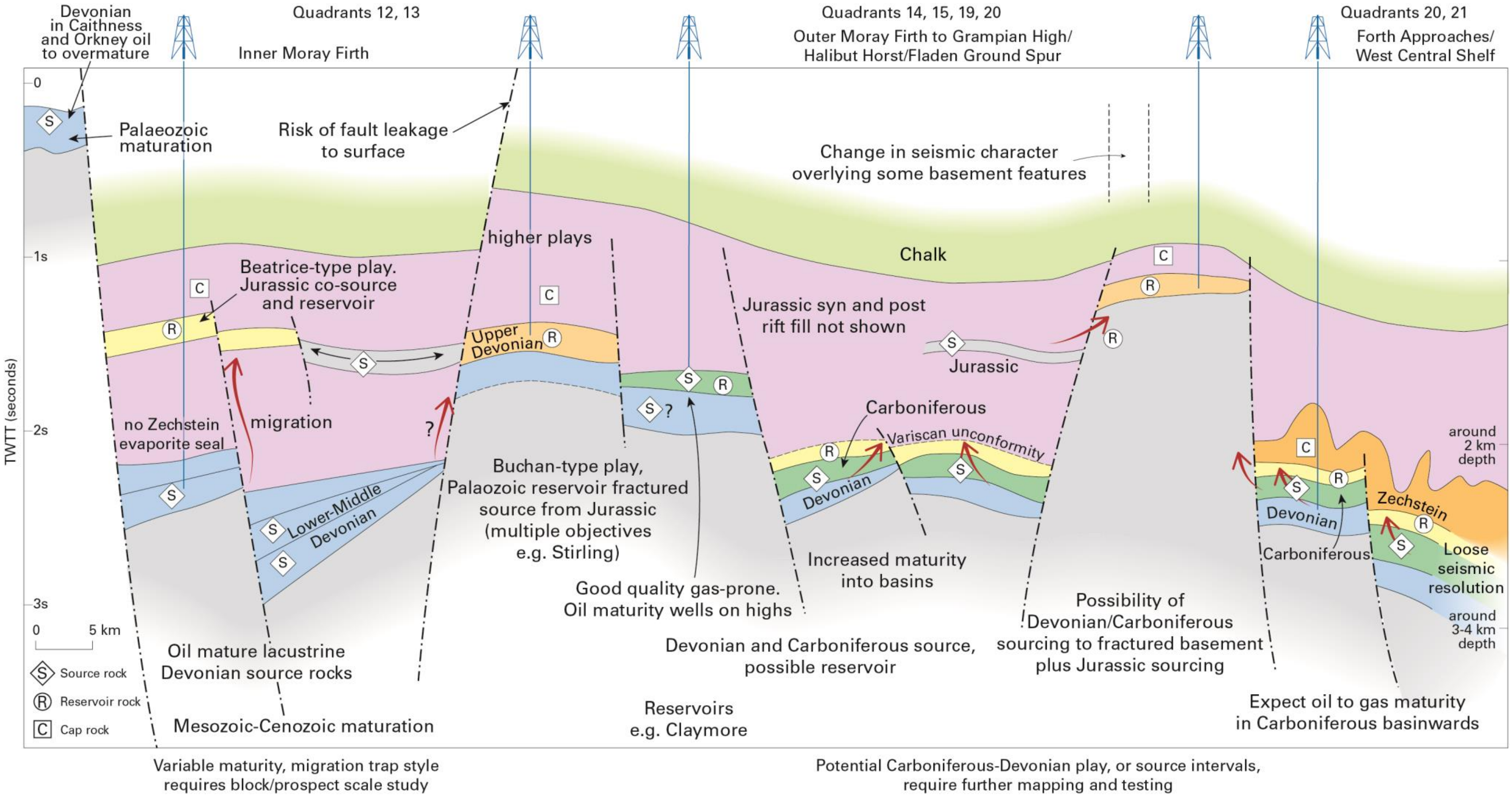


Figure 45 Cartoon summary of the Palaeozoic petroleum system elements and geometries observed across the Orcadian study area. Red arrows indicate potential migration pathways. Representative well locations and indicative scales are shown.

The wide variety of structural geometries, Palaeozoic source and reservoir intervals and possible migration pathways to Mesozoic traps are summarised on Figure 45.

Patruno and Reid (2015) highlight the role of Palaeozoic structure in the location of the Palaoecene (Cenozoic) age Kraken Field (Quadrant 9) in an anticline above an inverted Devonian structure. Further detailed mapping and understanding of Palaeozoic structure may have positive impacts on understanding of migration pathways and overlying traps within the Mesozoic and Cenozoic succession.

Seismic mapping and well data shown above have mapped greater extents of Devonian and Carboniferous source rock intervals than previously quantified. Source rock maturity is variable, as is modelled timing of hydrocarbon generation (Figure 46). The 'block and basin' structure of Quadrants 6 – 21 makes it difficult to study the thermal, burial and uplift history of a 'typical' well and further sample analysis and basin modelling is recommended to complement existing commercial reports (e.g. Robertson Research International, 2001). A promising area for further study is to the north-east and south-east of the Halibut Horst where the current dataset from wells drilled on highs indicates deepest Cenozoic burial to oil window maturity, with a Mesozoic to Cenozoic cover (Figure 46).

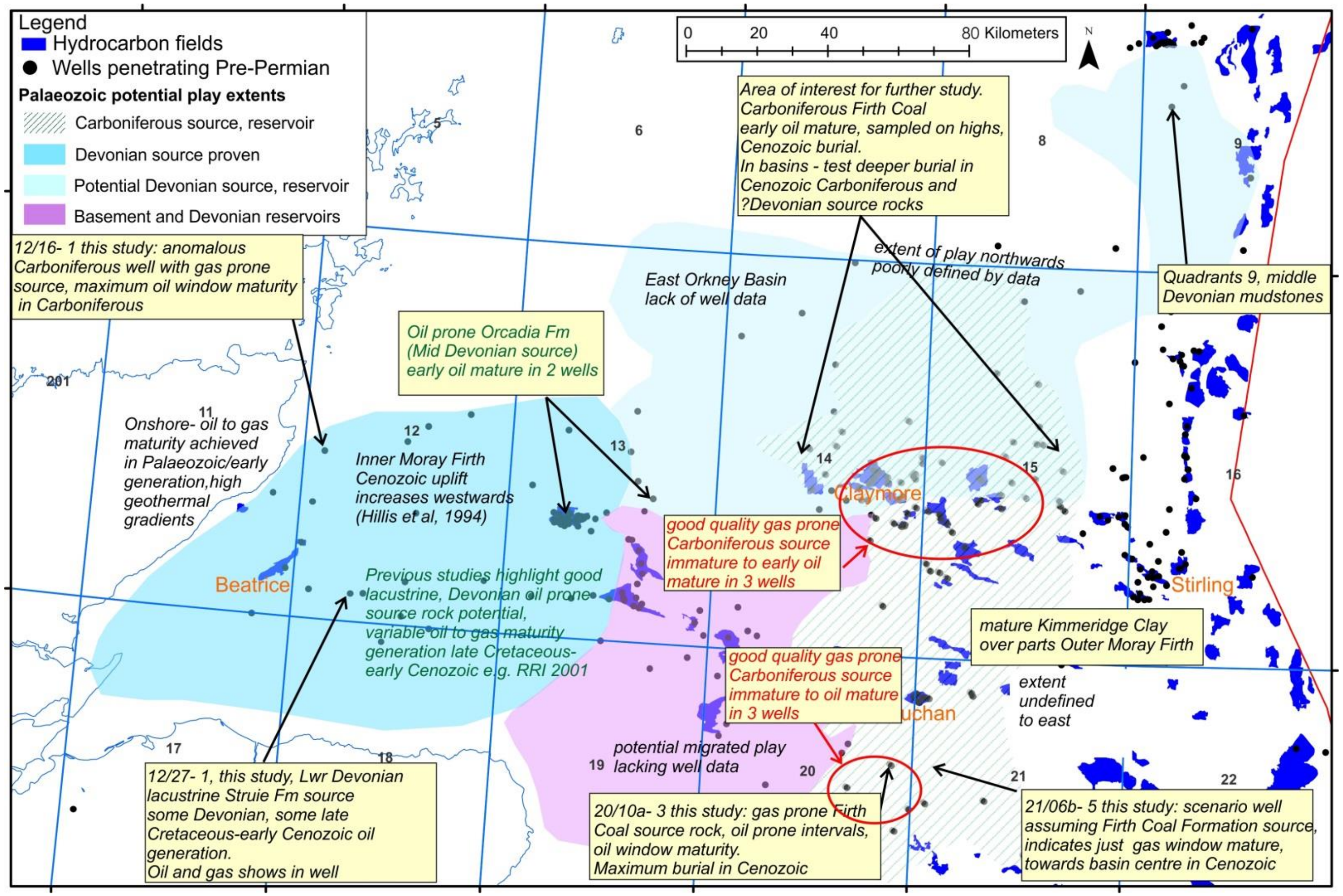


Figure 46 Summary of source rock maturity and modelled timing of maturation and generation at regional scale.

Key elements, knowns and risks are summarised in map view (Figure 47).

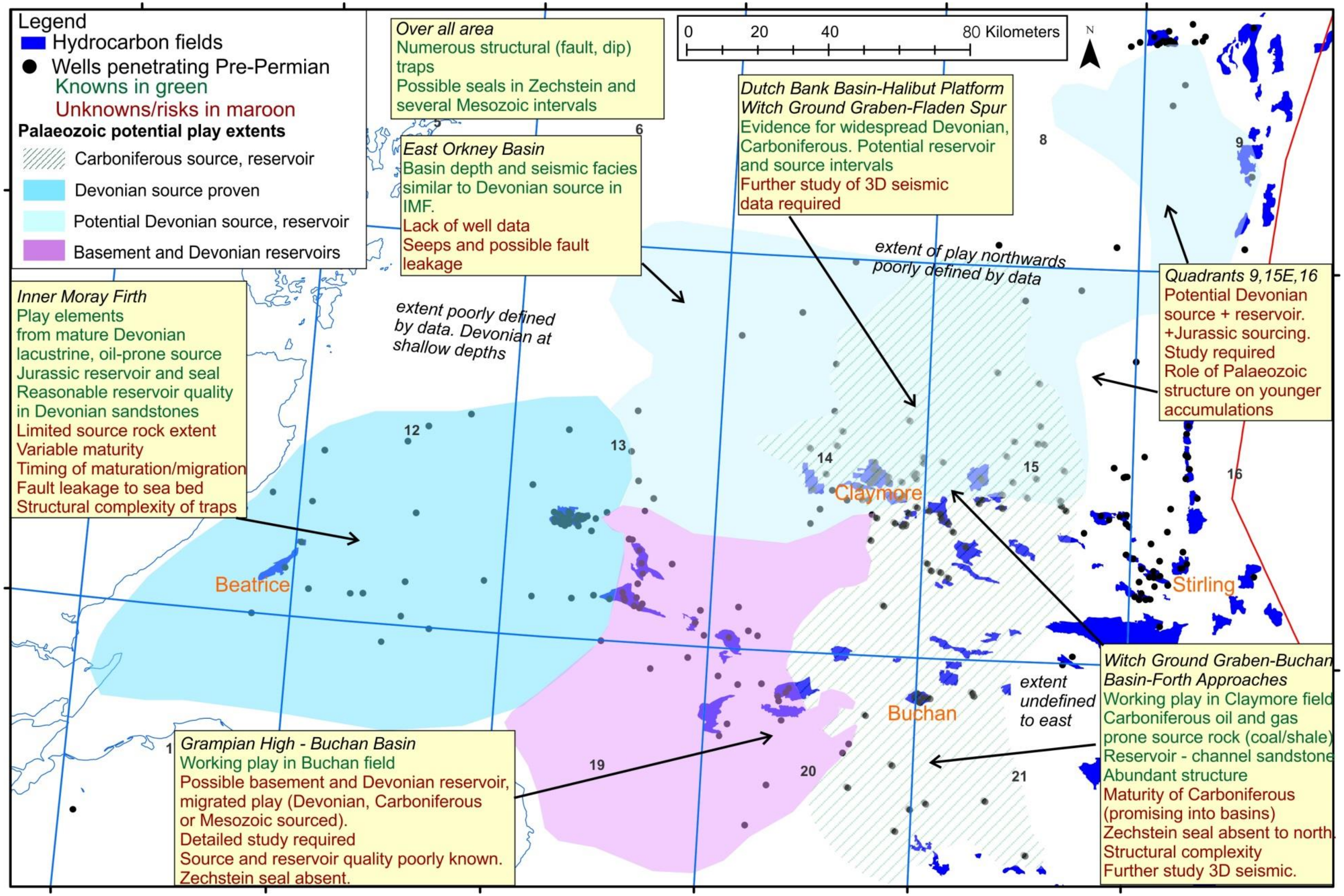


Figure 47 Summary map of knowns (green) and unknowns/risks (maroon) for the Palaeozoic petroleum system elements considered.

In conclusion, the Palaeozoic project study provides the data and interpretations to evidence Devonian and Carboniferous petroleum system elements that are widespread across Quadrants 11 – 15 and 19 – 21. The well, seismic, organic geochemisty and core analysis datasets constraining the interpretations are of variable vintage, density and resolution, leading to lower confidence in the overall petroleum system synthesis than for the areas surrounding the Mid North Sea High.

In addition, recent published work (Reid and Patruno, 2015; Patruno and Reid, 2015) highlights the likely continuation of the Palaeozoic system elements further east and north into Quadrants 8, 9, 16.

The petroleum systems are not contained within the Palaeozoic sequence with evidence for both (i) migration to Mesozoic reservoir/traps and (ii) migration of Jurassic-sourced oil to Palaeozoic reservoirs.

The involvement of Mesozoic source, reservoir and seal rocks offers opportunities for stacked plays (e.g. as proven in Claymore, Stirling) and for extension of prospectivity. For example, when considering the migration and trapping of Jurassic oil in and around the 'middle mature Kimmeridge' areas of the Witch Ground Graben and Buchan Basins (Figure 11), the possibility for trapping in Palaeozoic reservoirs should be evaluated, beneath the stratigraphically higher targets. Conversely, when evaluating Mesozoic and younger prospectivity, the contribution of Palaeozoic co-sourcing of oil and gas should be considered.

Key Devonian and Carboniferous source rock intervals are (Figure 3):

- The Lower Devonian Struie Formation
- The Middle Devonian Orcadia Formation and Eday Group
- The Visean-Namurian (lower to middle) Carboniferous Firth Coal Formation

Devonian lacustrine units are oil prone, Carboniferous fluvio-deltaic coals and mudstones are gas and oil prone (the productivity of thin oil prone layers requires further investigation).

Key Devonian–Carboniferous reservoir intervals are (Figure 3):

- The Upper Devonian Buchan Formation, possibly extending upwards to parts of the Tayport Formation
- The Visean-Namurian (lower to middle) Carboniferous Firth Coal and Fell Sandstone formations
- Possibilities for reservoir intervals within the Devonian Middle Eday Sandstone and Upper Strath Rory formations.

The dominance of a tilted fault block structural style across the area provides numerous opportunities for trapping. In southern parts of Quadrants 20 and 21 trapping at base Permian unconformity, or at base Zechstein appears possible. Over the remainder of the study area, Permian and Mesozoic reservoirs and seals require local evaluation. The structural complexity and variability in the succession necessitates more local studies on timing of maturation and migration.

8 Future work

Fields with a Palaeozoic reservoir in Quadrants 14, 15, 16, 20, 21, the oil and gas shows within the Carboniferous sequence in Quadrants 14, 15, 20, 21 and the structural trapping potential seen on the highest resolution seismic data (Arsenikos et al 2016; Reid and Patruno, 2015) indicate a potentially significant contribution of Palaeozoic strata to future prospectivity. A recommendation is made for further work on Jurassic sourced/Palaeozoic reservoirs and Devonian – Carboniferous sourced/post-Carboniferous reservoir prospectivity across Quadrants 8, 9 14, 15, 16, 20 and 21 (Figure 48, in green). Regional scale seismic interpretation on the best 3D datasets, organic geochemistry/maturity sample analysis and oil/gas typing studies would be required to better constrain regional scale basin modelling. Areas underlying the more deeply buried Mesozoic and Cenozoic successions may have greatest potential. These are not 'frontier' areas in the sense that they are heavily studied and licensed for Mesozoic and Cenozoic plays. However the potential of the underlying Palaeozoic succession is the 'deep frontier', and its structural influence on the younger play systems may be significant. Typing of oil and gas from fields and discoveries could determine whether there is a significant component of Palaeozoic co-sourcing more widely than the Inner Moray Firth.

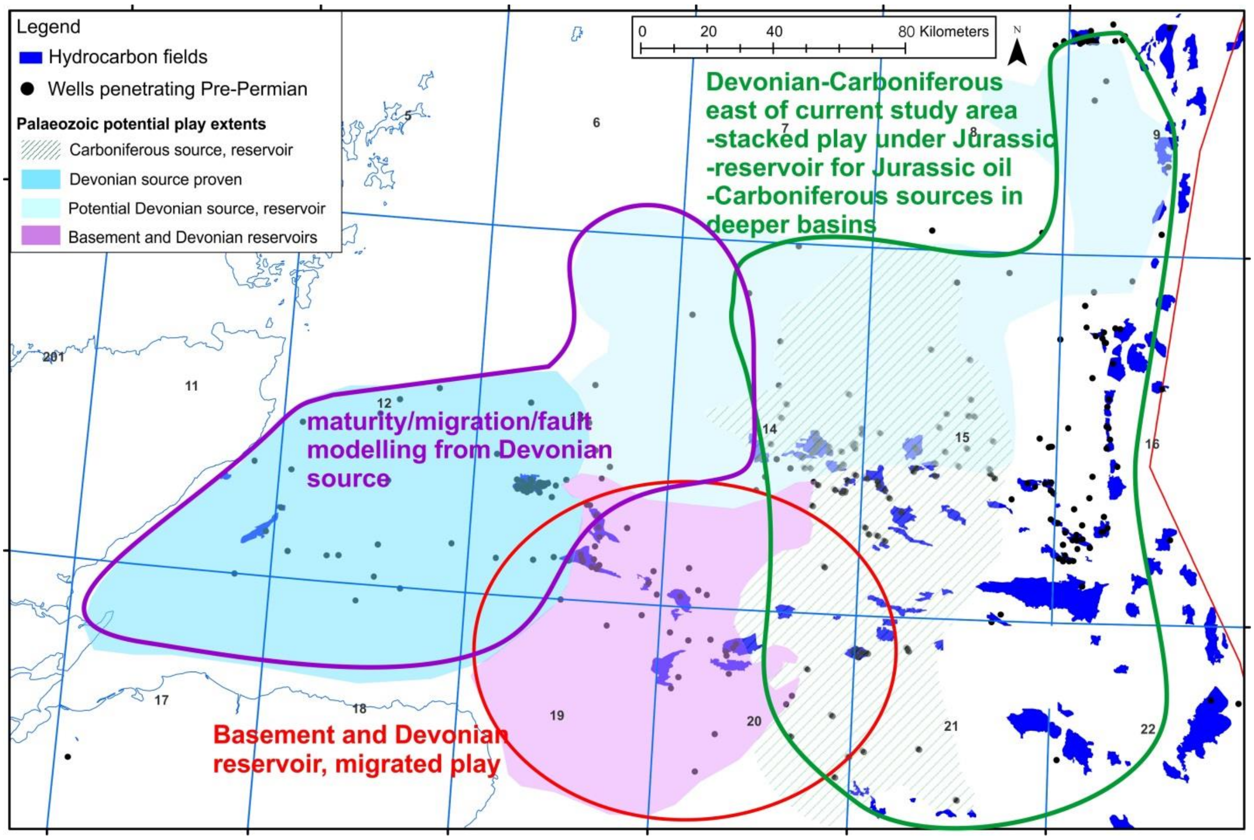


Figure 48 Map of the areas indicated for further work

This study has extended the mapping of several Devonian source rock units from the Inner Moray Firth to the northern side of the Halibut Horst/East Orkney Basin, (Quadrants 11, 12, 13, 14W). Future work could focus on wider basin modelling of maturity, migration routes and trapping/fault leakage (Figure 48).

In southern Quadrants 13, 14 and Quadrants 19, 20 further detailed seismic mapping, core analysis data and basin/migration modelling are required to further evaluate prospectivity of a 'migrated play' which could involve Palaeozoic and Jurassic sources in the adjacent basins, migrating up-dip to basement or Devonian or younger reservoirs (Figure 48).

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