British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Literature Review of Devonian Source Rocks and Devonian-Sourced Hydrocarbons in the Orcadian Basin

Energy and Marine Geoscience Programme

Commissioned Report CR/16/017

BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCE PROGRAMME

COMMISSIONED REPORT CR/16/017

Literature Review of Devonian Source Rocks and Devonian-Sourced Hydrocarbons in the Orcadian Basin

E Greenhalgh

Keywords

Report; Orcadian, Devonian, source rock, hydrocarbon, Beatrice.

Bibliographical reference

GREENHALGH, E. 2016. Literature Review of Devonian Source Rocks and Devonian-Sourced Hydrocarbons in the Orcadian Basin. *British Geological Survey Commissioned Report*, CR/16/017. 25pp.

Keyworth, Nottingham British Geological Survey 2016

BRITISH GEOLOGICAL SURVEY

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

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

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

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

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

British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB
Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

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

Acknowledgements

We would like to thank CGG for providing and allowing citations of the RRI report and BP for provision of numerous legacy reports. Mark Sugden and George Siavalas (Shell) are thanked for technical review of this report.

Contents

FIGURES

TABLES

Summary

This report summarises existing work on the Devonian source rocks and migrated oils in the Orcadian Basin. It aims to clarify the current literature with regards to the contribution of Devonian source rocks to proven hydrocarbon accumulations within the basin by providing a comprehensive summary of;

- the quality and maturity of the lacustrine source rocks;
- the evidence for Devonian oils in hydrocarbon fields, discoveries, shows and stains;
- perceived risks for Devonian-sourced plays.

Good quality oil-prone lacustrine source rocks are present in the Devonian both on- and offshore, and are believed to have co-sourced the three Inner Moray Firth oil fields – Beatrice, Lybster and Jacky. Thus an understanding of the distribution and burial history of the Devonian source rocks could be important in the search for new hydrocarbon discoveries in the region. The complex pre-, syn- and post-rift tectonic history has given rise to significant local variability in both the thickness of the Devonian section and the present-day thermal maturity. Offshore, determination of the extent of the Middle Devonian Orcadian Lake, the main source rock interval, is constrained by only a limited number of well penetrations of the Devonian interval centred on Quadrants 12 & 13, although an oil-correlation study by Robertson Research International (2001) suggested that Devonian source rocks may be developed as far east as Quadrant 15 and may therefore be more widespread than previously thought.

Studies have shown that Devonian-sourced oils have some key characteristics meaning they can confidently be differentiated from Jurassic-sourced oils. In particular, the presence of carotane and gammacerane (which can both be indicative of hyper-saline depositional environments), the absence of C_{28}-bisnorhopane (commonly found within Jurassic sourced oils), the relatively light carbon isotope ratios and depletion of C_{27} steranes are distinguishing features when contrasted to Upper Jurassic to Middle Jurassic sourced hydrocarbons.

Basin modelling studies suggest that onshore, the Devonian source rock experienced early hydrocarbon generation, reaching mid-late oil window thermal maturity by the Late Palaeozoic. Offshore, the preferred model is for Mesozoic generation with the onset of oil generation from the Devonian lacustrine source rocks in the Beatrice Field kitchen area in the Early Cretaceous, negating the need to invoke long-range migration from mature Jurassic mudstones to charge the Beatrice structure.

This report was completed before the Palaeozoic Project organic geochemistry work on the Orcadian area (Vane et al., 2016), to inform the scope of work on that study. As such, it does not integrate the results of the Palaeozoic organic geochemistry study. This report contains citations of donated proprietary and commercial reports.

1 Introduction

There are five proven source rocks in the Moray Firth area: Upper Jurassic (Kimmeridge Clay Formation); Middle Jurassic (Brora Coal Formation); Carboniferous (Firth Coal Formation); Middle Devonian (Orcadia Formation); and Lower Devonian (Struie Formation). On a regional scale, the Upper Jurassic and Middle Jurassic source rocks are considered to be most important, but locally the presence of good quality and mature Devonian source rocks could be key to future prospectivity. This is because the Devonian lacustrine shales of the Orcadian Basin have been proven to have good source potential (e.g. Robertson Research International, 2001; Marshall et al., 1985; Marshall, 1998; Marshall & Hewett, 2003; Peters et al., 1989), although the level of contribution of Devonian source rocks to the known hydrocarbon accumulations in the region is still debated. The Beatrice Field – the most significant discovery in the Inner Moray Firth which has produced 27 million m^3 (to end 2014, figure from DECC) from Middle and Lower Jurassic sandstones in a faulted anticline – is widely considered to be sourced in part from the Devonian (e.g. Curran, 1987a; Halliburton Geo Consultants, 1990; Peters et al. 1989). Additionally, the Devonian is also thought to contribute oils to the Lybster (Robertson Research International, 2001) and Jacky fields (Curran & Fischer, 1987). Optimal conditions for Devonian-sourced oils exist around well 12/27- 1 and the Beatrice Field (Curran, 1987a), however nearby well 12/26- 1 is thought to have failed due to lack of charge (Hogan et al., 1978), demonstrating the local variability within the play. This report comprises a review of the Devonian source rock potential and migrated oils attributed to a Devonian source from published papers, well reports and confidential company reports.

1.1 TECTONIC HISTORY OF THE ORCADIAN BASIN

A brief overview of the tectonic history of the Orcadian Basin is given here; for a more comprehensive summary (and references for further reading) see Marshall & Hewett (2003). Extension during the Mid-Silurian – Early Devonian eventually led to the gravitational collapse of the Caledonian Orogenic Belt north of the Highland Boundary Fault, generating a series of small half-grabens. Early Devonian alluvial, aeolian and lacustrine sediments were locally deposited into these half-grabens. Continued extension through to the Middle Devonian resulted in these structures coalescing into a single large system - the Orcadian Basin - and the sedimentary system became dominantly lacustrine (Marshall & Hewett, 2003; Peters et al., 1989). The lakes alternated between shallow playas that flooded episodically, and deeper lakes that became ‘permanently’ established for thousands of years. The major Middle Devonian depocentre was located in the Caithness & Orkney areas where greater than 3960 metres of cyclic lacustrine & fluvial sediments were deposited (Halliburton Geo Consultants, 1990). Organic and inorganic geochemistry data support a deep, stratified, lake system with high levels of bioproductivity (Duncan & Hamilton, 1988). In latest Mid-Devonian to Late Devonian times, the basins became post-rift in character and evolved to a more open drainage system with sediment deposition from a large river system, with a major switch in the depocentre from Caithness/Orkney to the Outer Moray Firth (Halliburton Geo Consultants, 1990). Post-rift, the area experienced significant deformation during a period of inversion in the Permian and rifting in the Upper Jurassic (Peters et al., 1989), and underwent a phase of uplift in the Early Tertiary (Marshall, 1998).

1.2 FIELDS

Within the Orcadian Basin, the Beatrice, Jacky and Lybster oil fields are thought to have a Devonian contribution. All three fields produce from sandstones of the Mid Jurassic Beatrice Formation. Within the study area, only the Buchan Field (blocks 20/05 & 21/01), located on the southern side of the Witch Ground Graben, produces hydrocarbons from a Devonian reservoir but is sourced from the Upper Jurassic (Edwards, 1991). The Devonian reservoir rocks are typically low-permeability, well-cemented fluvial sandstones from which production is enabled by fracturing, especially in proximity to faults (Marshall & Hewett, 2003).

2 Quality and maturity of lacustrine source rocks of the Orcadian Basin

2.1 PRESENCE OF DEVONIAN SOURCE ROCKS

Devonian oil-prone lacustrine source rocks are present both onshore and offshore Inner Moray Firth, as indicated by outcrop and well data (e.g. Marshall & Hewett, 2003; Marshall et al., 1985; Marshall, 1998; Peters et al., 1989; Robertson Research International, 2001; Peters et al., 2005; Trewin, 1989; Figure 1). The source rocks are dark, organic-rich laminated units and are also known as 'fish beds' (Duncan & Hamilton, 1988). The general distribution of Devonian sediments indicates isolated mud-rich lacustrine basins in the Lower Devonian, with Middle Devonian deposition being more widespread (Halliburton Geo Consultants, 1990). Onshore, Lower Devonian-aged source rocks outcrop in the Strathpeffer area, and Middle Devonian-aged source rocks (Achanarras equivalents) are found at the Blackpark area, Caithness, Orkney, Sutherland and Cromarty (Curran, 1987a; Robertson Research International, 2001; The Geochem Group, 1986).

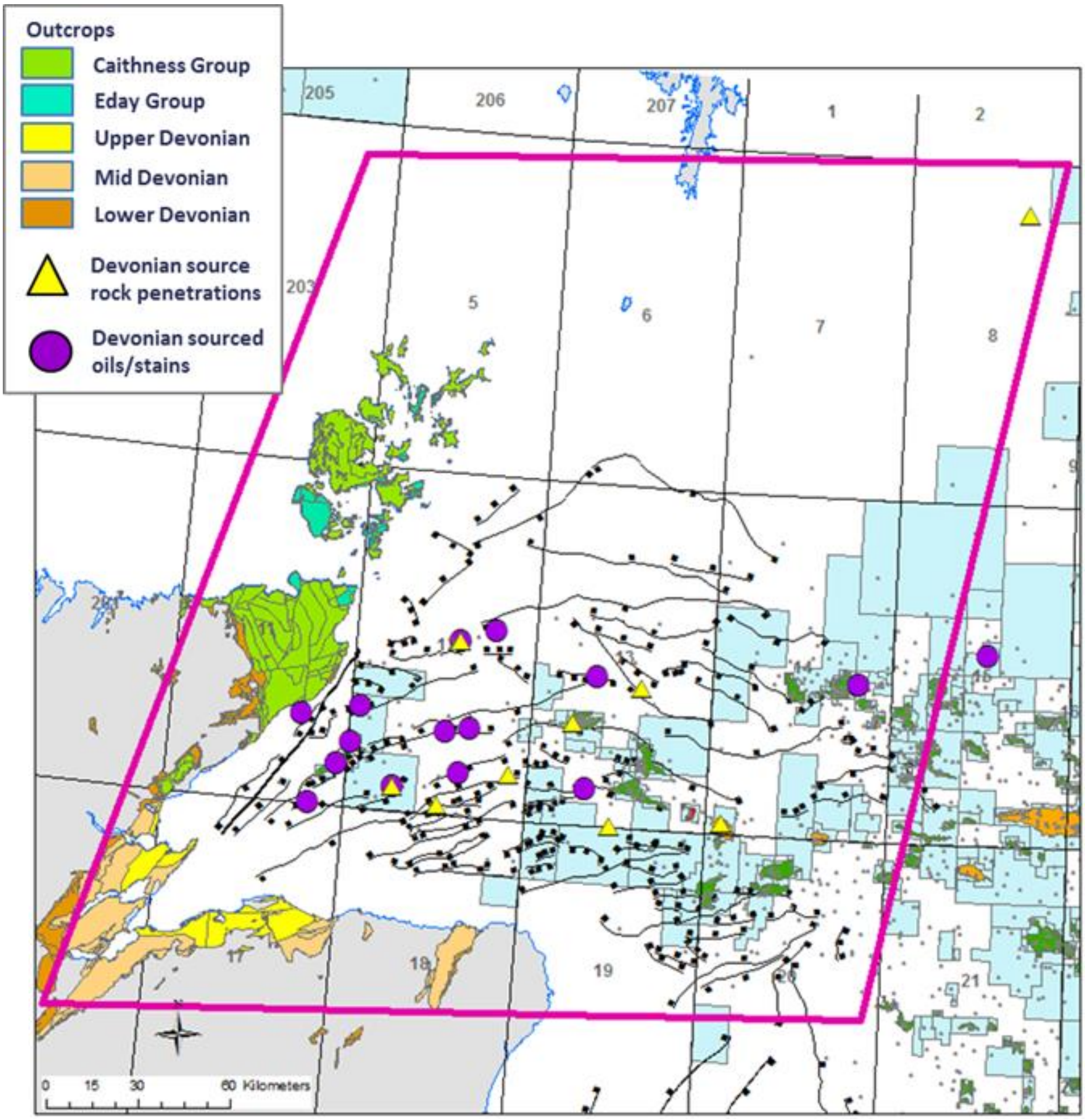

Figure 1 Map showing location of wells with Devonian source rock penetrations, wells with reported Devonian sourced oils/stains and onshore Devonian outcrops. Pink line shows extent of the study area considered in this review. Outcrops from BGS 1:625000 scale DiGMapGB ©NERC.

Offshore, the southern extent of the Middle Devonian Orcadian Lake is thought to be in the southern parts of Quadrants 11-15, solely determined from the typing of oils/stains (Robertson Research International, 2001). However this is supported by wells 13/24-1 and 13/28-1 that encountered Devonian conglomeratic/alluvial sands, indicative of a lake margin depositional environment (Halliburton Geo Consultants, 1990). The total Devonian section exceeds 5 km thickness in places (Robertson Research International, 2001); the Middle Devonian, comprising of cyclical lacustrine and fluvial deposits is the thickest section, with the best development of source rock (Edrich, 1980). The lacustrine sediments are either cm-scale interbeds of mudstones, siltstones and fine-grained sandstones or sub-mm scale alternations of clastic, carbonate and organic matter (Edrich, 1980; Peters et al., 2005). The laminites have greater lateral continuity and are stratified, indicating deposition in anoxic conditions and are therefore more likely to contain good source potential.

2.2 SOURCE ROCK QUALITY

TOC, HI, S1 & S2 measurements (see Vane et al. (2016) for table of organic geochemistry parameters) indicate intervals of moderate to good oil-prone source potential within the Devonian (Figure 2). Lower and Middle Devonian lacustrine source rock intervals contain present-day TOC values of up to 6%, with one-fifth of all facies containing TOC > 1% (Marshall et al., 1985; Curran, 1987a; Cornford, 2009; Figures 2a & 3). The maximum present-day TOC of 3.2% in well 12/27-1 equates to an original TOC of > 5% when corrected for maturity (Marshall, 1998); other studies do not comment on the original source rock quality. Well 12/27-1 also encountered a thick mudstone sequence in the Upper Devonian with HI values up to approximately 400 mg/g, indicating potential for oil (Curran, 1987a). Vertical variation in TOC within the Devonian section is due to lake-level changes (Marshall & Hewett, 2003). HI > 500 mg/gC are recorded from outcrops and offshore wells (Figures 2b & 3), with Lower and Middle Devonian source rocks containing dominantly oil-prone type I kerogen (Peters et al., 1989; Trewin, 1989; Peters et al., 2005). Duncan & Hamilton (1988) determined from a biomarker study that the kerogen has an algal source and was deposited in an anaerobic environment with elevated salinity. The distribution of source rocks with good potential is not uniform, although some of the best values are associated with the thicker lacustrine deposits of the Achanarras fish bed (Trewin, 1989).

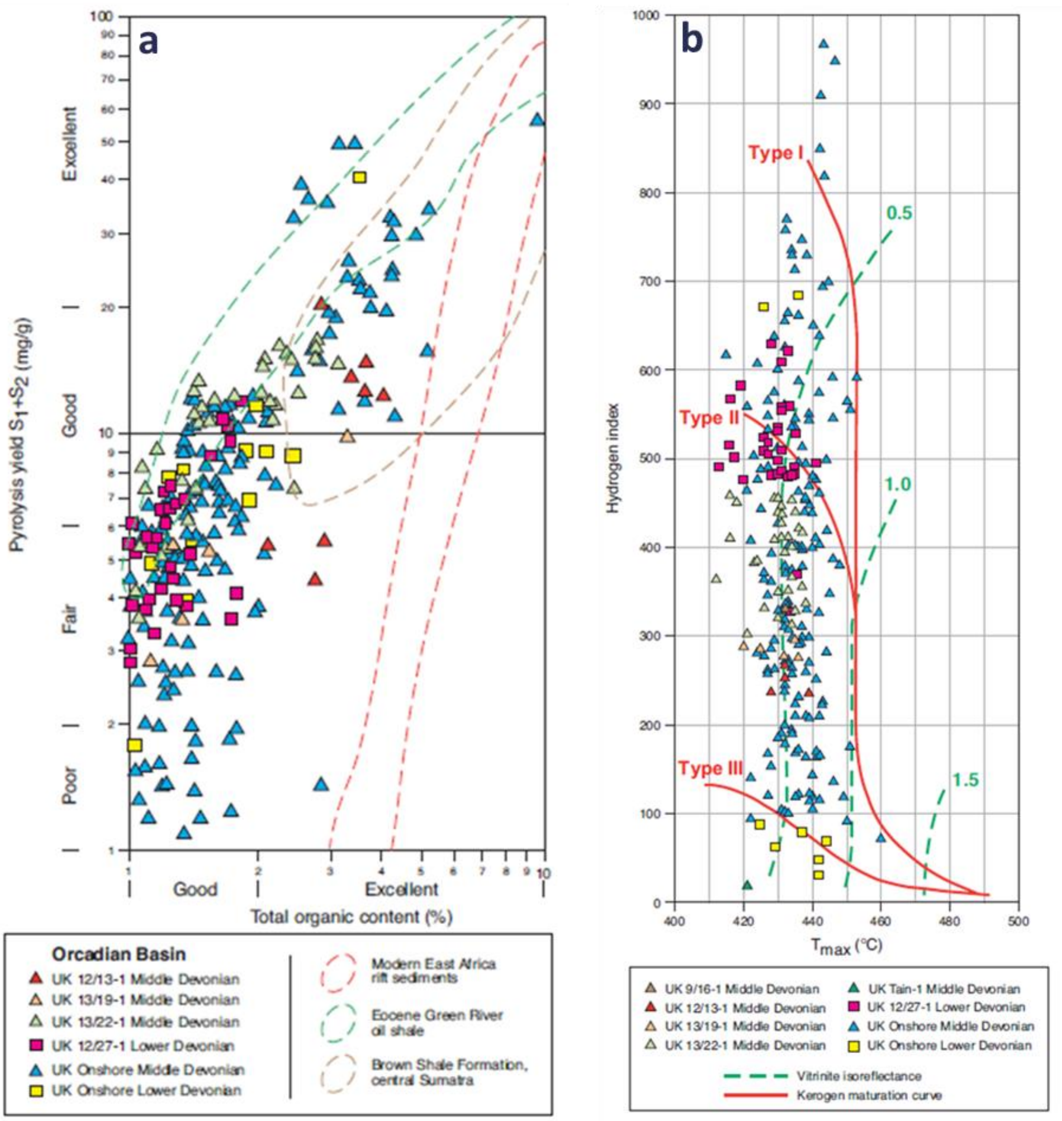

Figure 2 a) Graph of TOC vs Pyrolysis Yield and b) Plot of Tmax vs HI for Lower and Middle Devonian source rocks. Both figures from Marshall & Hewett (2003), reproduced with permission of The Geological Society, London.

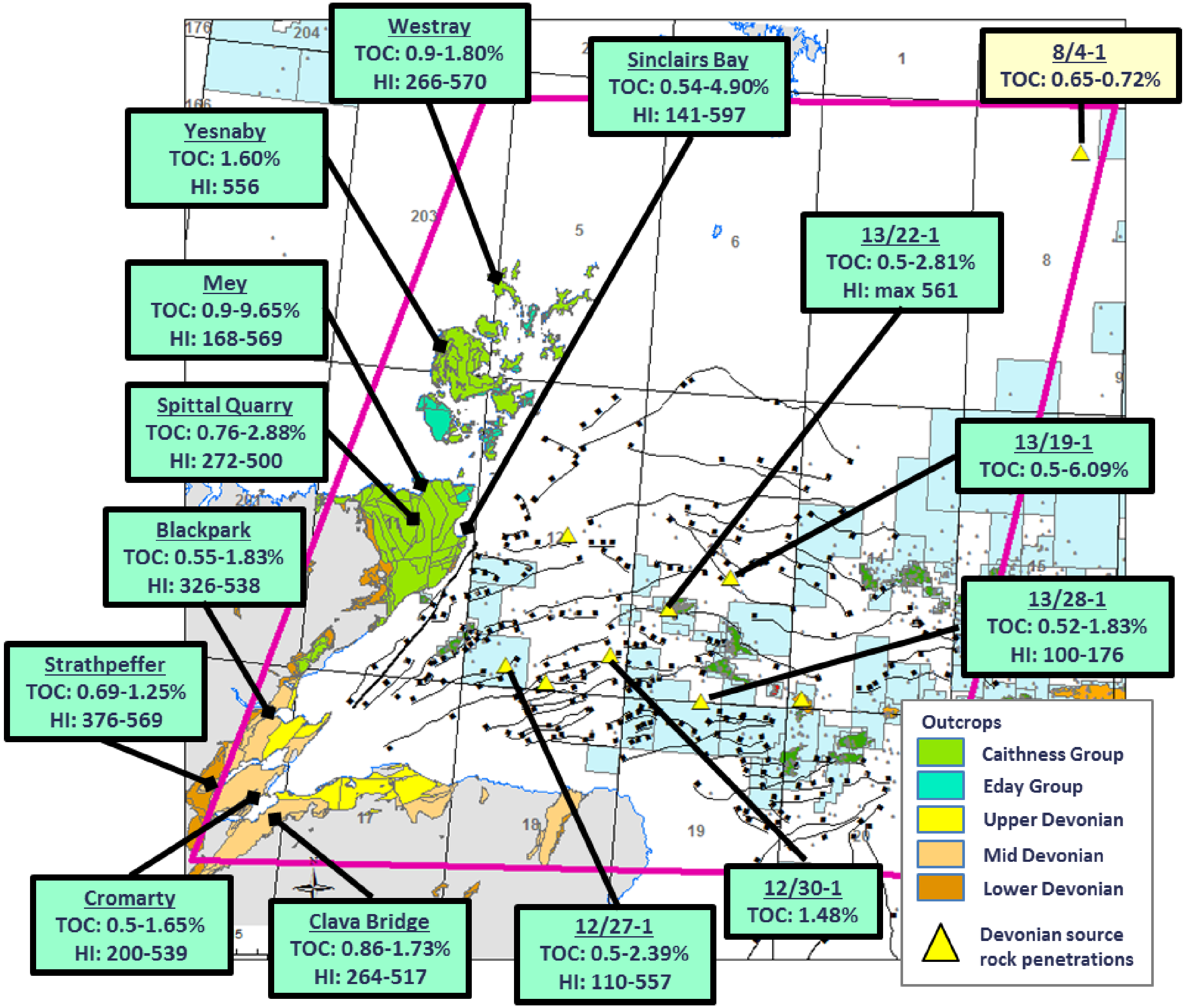

Figure 3 Summary of TOC & HI for Devonian source rock intervals encountered in wells and outcrops. Data from Robertson Research International (2001); Marshall & Hewett (2003); Bailey et al. (1990); Marshall (1998).

2.3 SOURCE ROCK MATURITY

The maturity of the Devonian succession varies regionally from early 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, and in wells 14/6- 1 and 14/30- 1 (Curran, 1987b; Trewin, 1989; Robertson Research International, 2001; Figure 4). Onshore, the highest maturities are associated with contact metamorphism by Devonian plutons (Hillier & Marshall, 1992). On a local scale, the Devonian source rock could be (present-day) at differing levels of maturity in juxtaposed areas due to complex tectonics resulting from post-rift inversion (Robertson Research International, 2001; Hillier & Marshall, 1992). For well 12/27- 1, vitrinite reflectance data indicate the Devonian section ranges from early mature to gas mature present-day, with an overall trend of increasing maturity with depth (Halliburton Geo Consultants, 1990). A similar trend is observed in the Devonian section of well 12/29- 2, which ranges from early mature at the top of the section to oil-mature in the Lower Devonian (Hewett, 1993). At well 11/30- 6, the Devonian maturity has the same trend as the Jurassic whereas for well 13/22- 1 a marked discontinuity between the maturity trends of the Jurassic and Devonian sections is observed (Curran, 1987b). An area of extremely high maturity is observed along the Great Glen Fault, thought to be related to shear zone metamorphism (Hillier & Marshall, 1992). Estimates of source rock maturity are obtained from vitrinite reflectance, thermal alteration index (TAI) and spore colour data. However, maturity determined solely from vitrinite reflectance data could be an under-estimate as these values are suppressed by the presence of amorphous organic matter (AOM; Marshall et al., 1985), which is prevalent in the Devonian lacustrine source rocks. A study by Marshall (1998) on vitrinite reflectance values in the Orcadian Basin suggests that the values in AOM are on average reduced by 0.69 times the unsuppressed equivalent. Additionally, Peters et al. (1989) noted that measured vitrinite reflectance data may only be approximate due to low vitrinite concentrations within the organic-rich intervals, but thermal maturation-dependent biomarker data may be the best indicator of maturity.

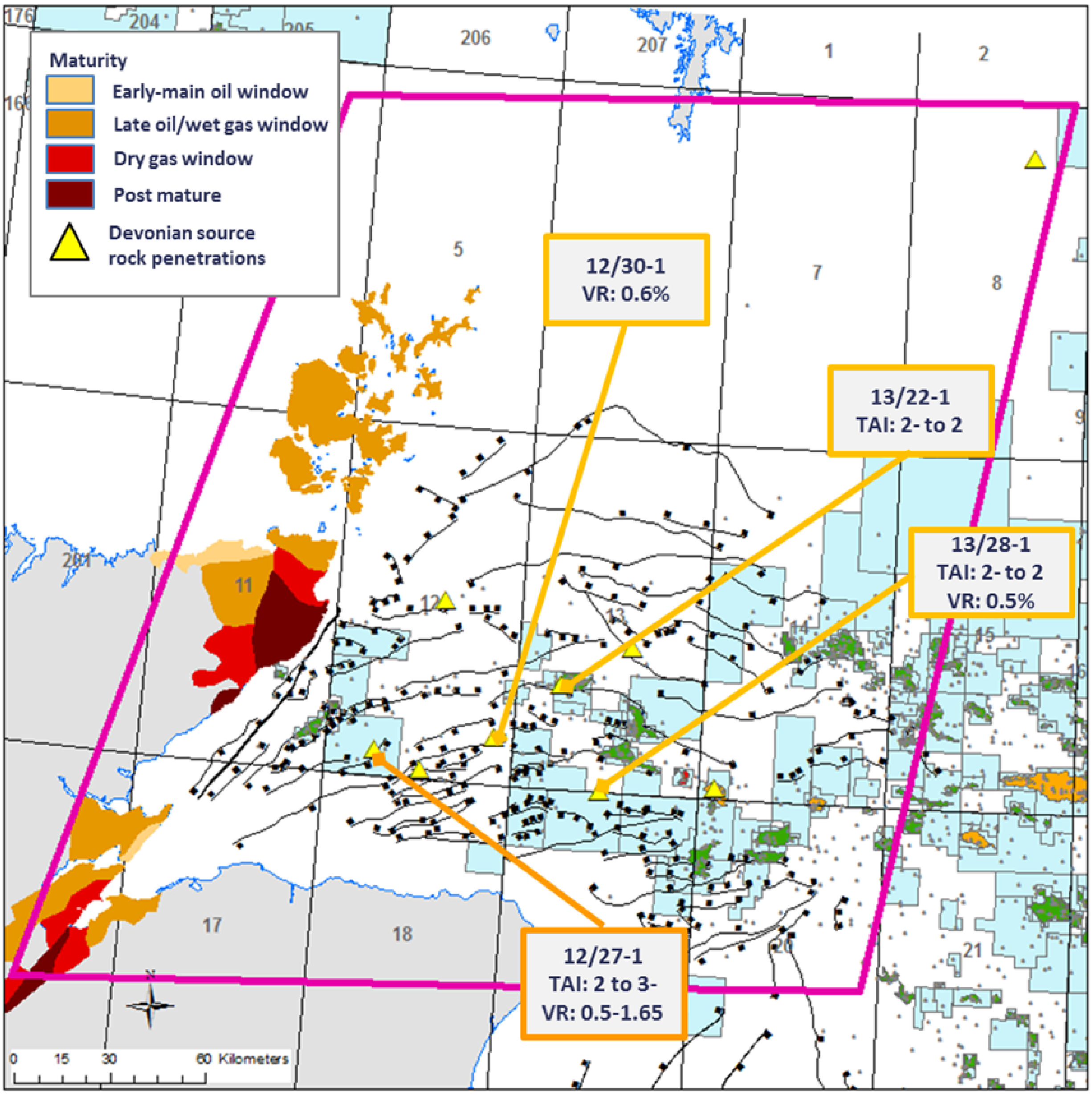

Figure 4 Maturity of Devonian source rock. Data compiled from Robertson Research International (2001); Marshall (1998); Marshall & Hewett (2003); Hillier & Marshall (1992).

3 Evidence for Devonian-sourced hydrocarbons

3.1 CHARACTERISTICS OF DEVONIAN-SOURCED OILS

Several studies have undertaken oil-source rock correlations in the Orcadian Basin (e.g. Curran, 1987a; Bailey et al., 1990; Peters et al., 1989; Peters et al., 2005). It has been proposed that a Devonian source can be confidently distinguished from an Upper Jurassic source due to several distinct differences in carbon isotope ratios, hopane/sterane ratio and biomarkers (Table 1; Figures 5 & 6). Characteristic biomarkers for the Devonian include carotane which is indicative of organically rich, hypersaline lacustrine or highly restricted marine depositional environments (Peters et al., 2005) and gammacerane which is often associated with hypersaline environments, neither of which are present in significant quantities in Upper Jurassic-sourced oils (Marshall & Hewett, 2003). Conversely, the C_{28} bisnorhopane biomarker, which is commonly present in Kimmeridge Clay Formation sourced oils, is routinely absent in what is thought to be Devonian sourced oils (Peters et al., 1989).

	Devonian	**Upper Jurassic**
Carotane (m/z 123)	Abundant	Not significant
Carbon isotope ratios	Usually lighter than -31‰ (range -31 to -35.6‰)	Usually heavier than -31‰ (range -25 to -31‰)
C_{27} ββ steranes (m/z 218)	Depleted relative to C_{28} & C_{29}	Not depleted
C_{28} bisnorhopane	Absent	Relatively Abundant
C_{29} steranes	Dominant	
C_{30} triterpane	Low-moderate concentrations	Generally absent
C_{30} steranes	Absent	Abundant
Gammacerane (m/z 191)	Moderate concentrations	Low concentrations
Diacholestanes (m/z 217)	Depleted	Not depleted
Diasteranes	Depleted	
Hopane/sterane ratio	Higher (bacterial dominated)	Lower (algal dominated)
C_{33}-C_{35} hopanes	Low concentrations	

Table 1: Comparison of distinguishing features for Devonian and Upper Jurassic oils (summarised from Curran, 1987a; The Geochem Group, 1986; Peters et al., 1989).

3.2 OIL DATA

3.2.1 Onshore

Bitumen-like material in veins, on joint planes or as porosity filling is observed in Devonian outcrops at: the northern tip of Black Isle, on the southern shore of the Moray Firth and in fractures in Spitall & Achanarras Quarries (The Geochem Group, 1986), in Devonian lacustrine rocks at Strathpeffer and in the Lower Eday sandstone of Orkney (Curran, 1987a). Bitumen and seeps present onshore in Orkney and northern Caithness have been correlated with Devonian source intervals due to the common light carbon isotope values (Edrich, 1980; Parkinson, 1983). An oil-cemented Devonian sandstone breccia found at Brora shows evidence for mixing of two oils - a Devonian lacustrine oil and a probable Middle Jurassic source (Peters et al., 1999; Peters et al., 2005).

3.2.2 Offshore

Significant oils/shows showing the presence of carotane, possibly indicating a Devonian origin (Peters et al., 1989), are found in several wells offshore, centred around Quadrants 12/13 (Figure 7). Traces of oil recorded within sandy intervals of the Lower Devonian Struie Formation in well 12/27- 1 have been correlated with outcrops at Strathpeffer (Marshall, 1998). In wells 13/17- 1 and 13/27- 1 carotane is present alongside the bisnorhopane biomarker indicating a Jurassic Kimmeridge Clay Formation/Brora Coal Formation contribution suggesting a mixed source for the oil shows (Robertson Research International, 2001).

Results from a study by Robertson Research International (2001) indicate that in the southern parts of Quadrants 12-14, the API gravity is locally lighter than would be expected from Jurassic source rocks alone, suggesting a possible more mature, deeper, source rock is present. Further, gases in the North Buchan Graben/South Halibut Basin (block 14/26) are of higher maturity than the Kimmeridge Clay Formation in that area; as long-range Jurassic gas migration is considered unlikely, a stratigraphically deeper source from the Devonian is inferred (Robertson Research International, 2001). In well 14/20b- 19, an oil stain from a core at 9433' depth contained carotane, as did extracted oil from cuttings from well 15/13- 2 (Robertson Research International, 2001) – again indicating Devonian sourced hydrocarbons. However, the Kimmeridge Clay Formation is thought to source nearby oil fields including Claymore (Harker et al., 1991), Highlander (Whitehead & Pinnock, 1991), Tartan (Coward et al., 1991) and Piper (Schmitt & Gordon, 1991).

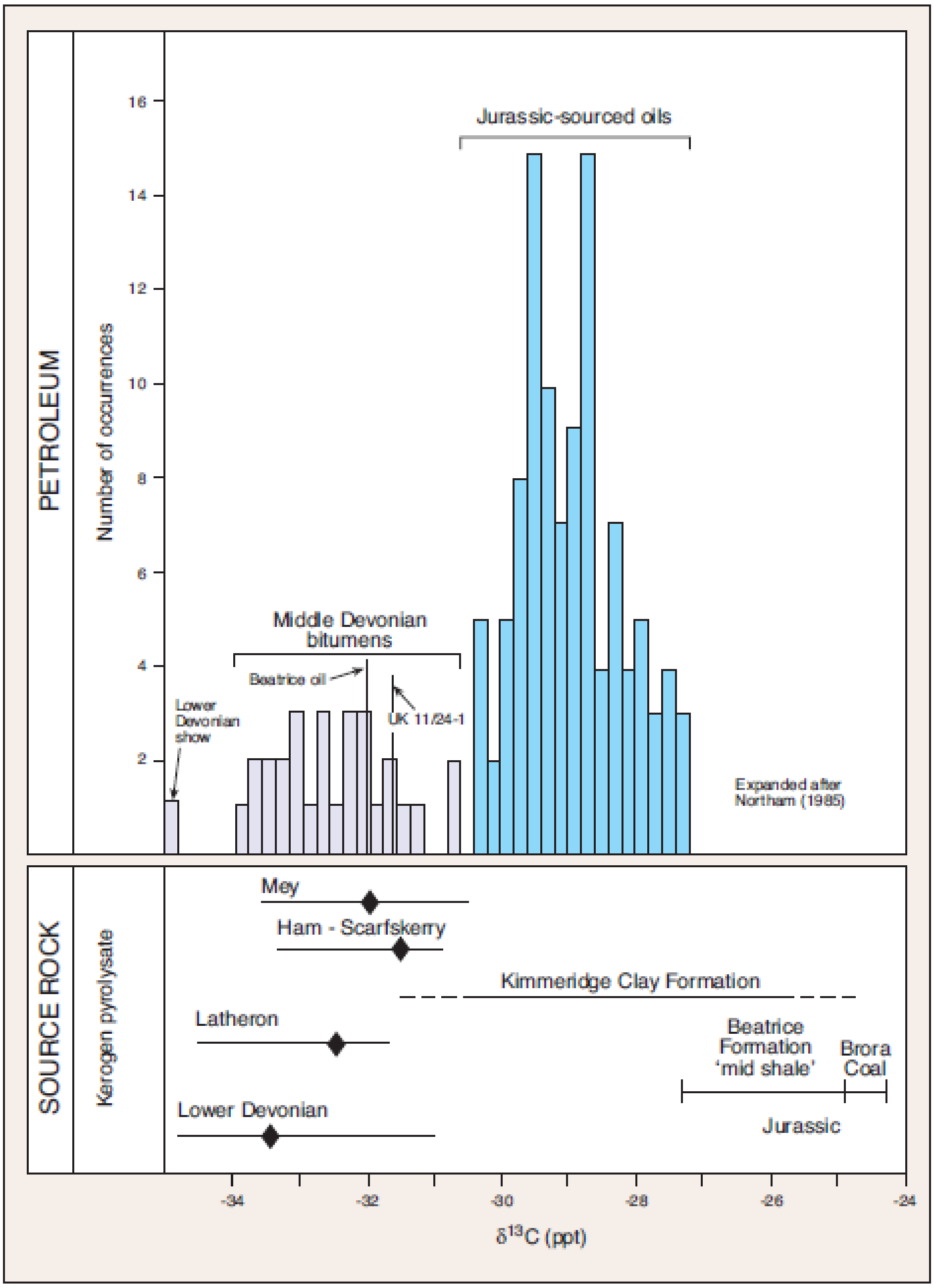

Figure 5: Comparison of carbon-isotope compositions for Devonian source rocks/oils and Jurassic source rocks/oils (Marshall & Hewett, 2003), reproduced with permission of The Geological Society, London.

3.3 THE BEATRICE FIELD

Beatrice oil differs from other North Sea oils on the basis of bulk geochemistry, isotopic signature and biomarker distributions (Figure 8; Duncan & Hamilton, 1988; Peters et al., 1989; Mackenzie et al., 1984). It also has a high wax content (Mackenzie et al., 1984; Peters et al., 1989; Marshall, 1998). The Beatrice Field oil has been variously attributed to the Lower Jurassic (Hogan et al., 1978), Middle Jurassic (Edrich, 1980), Upper Jurassic (Mackenzie et al., 1984), the Middle Devonian (Bailey et al., 1990) and a mixture of Devonian and Middle Jurassic, with the Jurassic being predominant (Curran, 1987a) or the Devonian being predominant (Halliburton Geo Consultants, 1990, Peters et al, 1989; Peters et al., 2005).

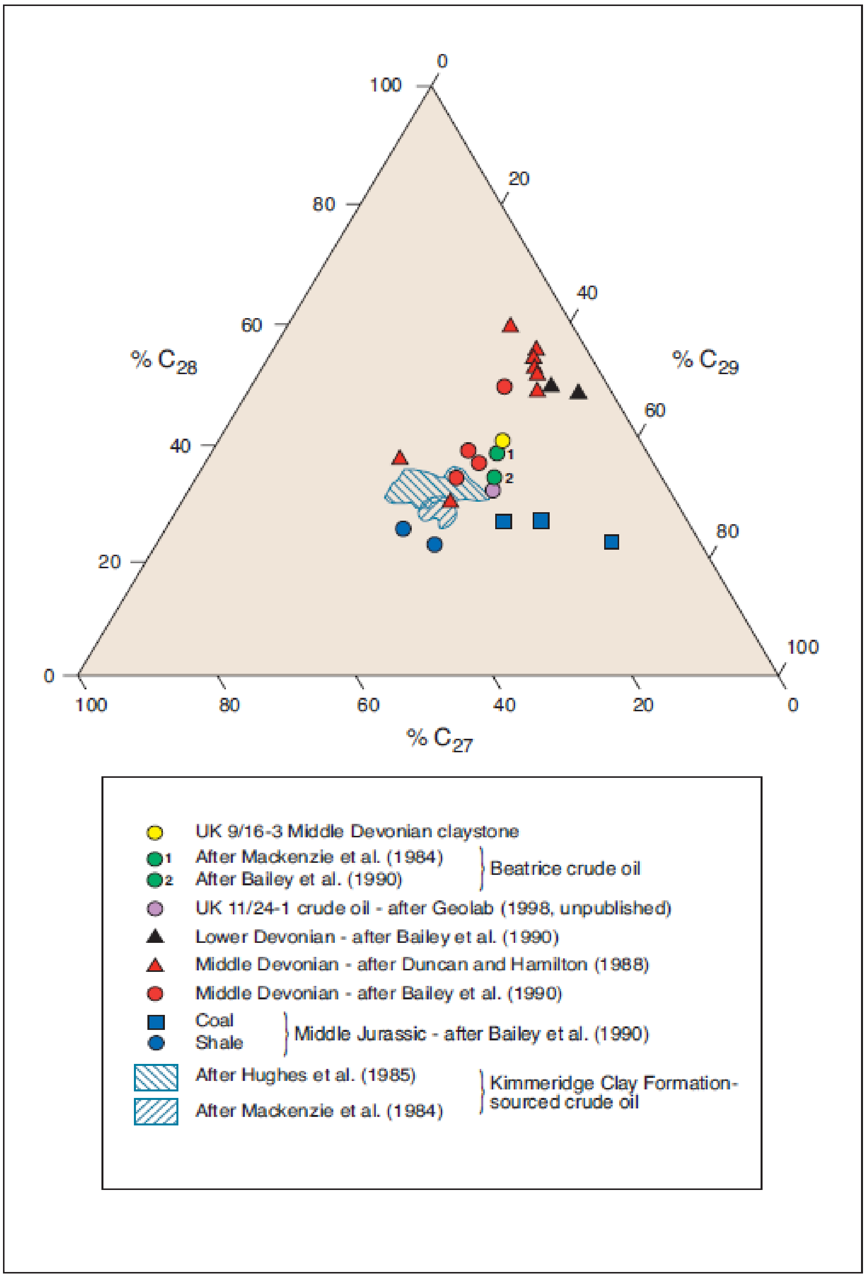

Figure 6: Comparison of sterane ratios for Devonian and Jurassic source rocks/oils (Marshall & Hewett, 2003), reproduced with permission of The Geological Society, London.

Early work suggested the Lower Jurassic sediments are a potential source for Beatrice oil due to their high TOC and close association with the reservoir interval (Hogan et al., 1978). The same report considered the Devonian to be over-mature in the region (based on structural history) and thought late generation of a waxy immature oil from the Devonian unlikely. A lagoonal/lacustrine Middle Jurassic source was proposed based on similarities between the Beatrice crude and Carboniferous oils of the Midland Valley (Weston & Winstanley, 1983). Mackenzie et al (1984) proposed the Upper Jurassic Kimmeridge Clay Formation as a source for Beatrice, invoking migration from a kitchen close to the Great Glen Fault; however, since the Kimmeridge Clay Formation is immature in the vicinity surrounding the Beatrice Field it is not, therefore, considered as a potential source by others (Peters et al, 1989; Stevens, 1991).

Bailey et al. (1990) proposed a Middle Devonian source for the Beatrice oil based on correlation of the carbon isotopes and biomarker data with the Middle Devonian Upper Caithness Flagstones onshore. Other studies support this correlation between Beatrice oil and Devonian source rocks to match the observed GC-MS, but a Middle Jurassic co-source is required to match the isotope values, which are considered too heavy to be solely Devonian (e.g. Curran, 1987a; Curran & Fischer, 1987; The Geochem Group, 1986; Halliburton Geo Consultants, 1990; Peters et al., 2005). Very low amounts of desmethyl C30-steranes in the Beatrice oil preclude significant input from marine organic matter (Peters et al., 1989).

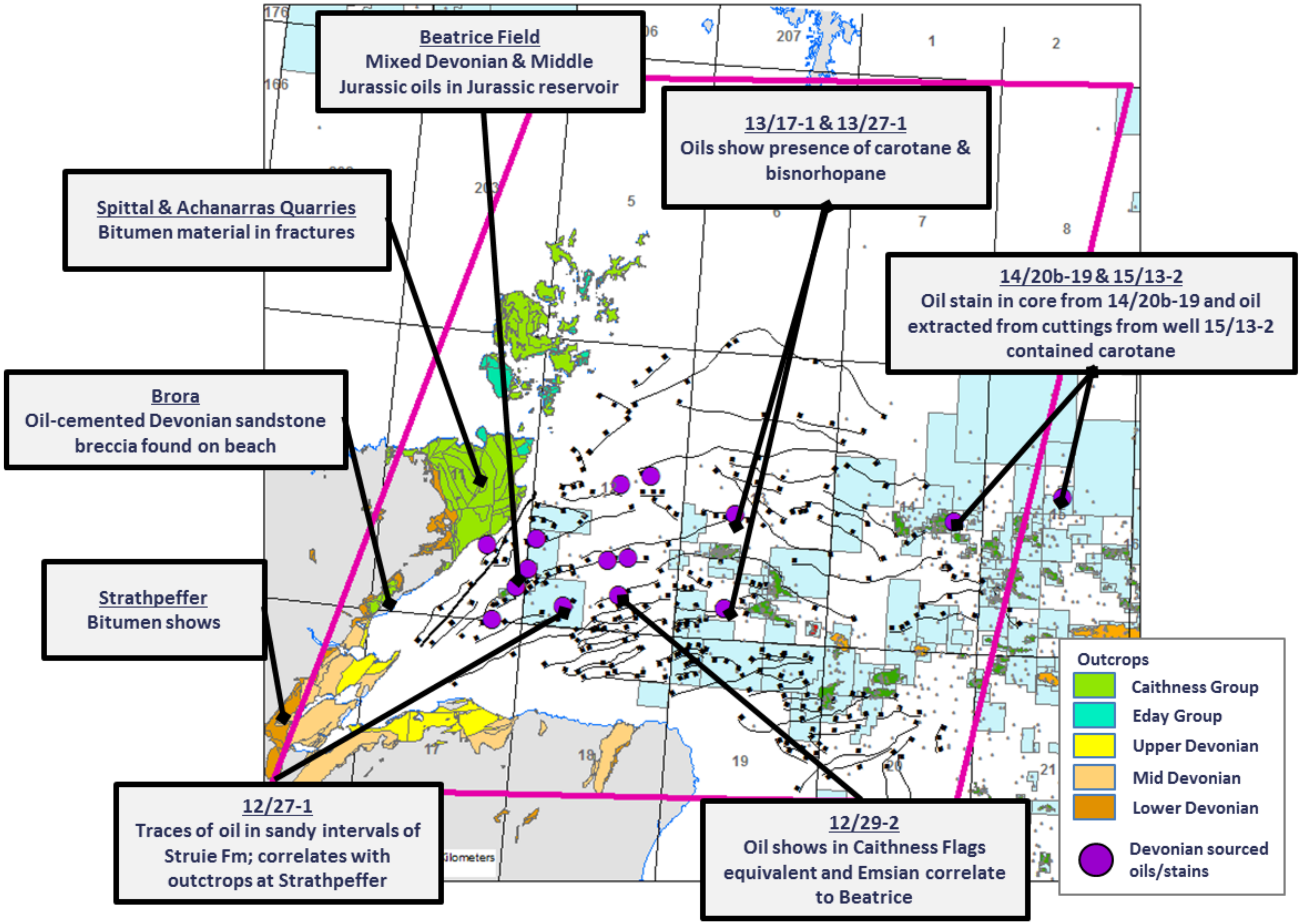

Figure 7: Distribution of reported Devonian-sourced oils/stains. Data summarised from Robertson Research International (2001); Peters et al. (1999); Hewett (1993); Marshall (1998); The Geochem Group (1986); Curran (1987a).

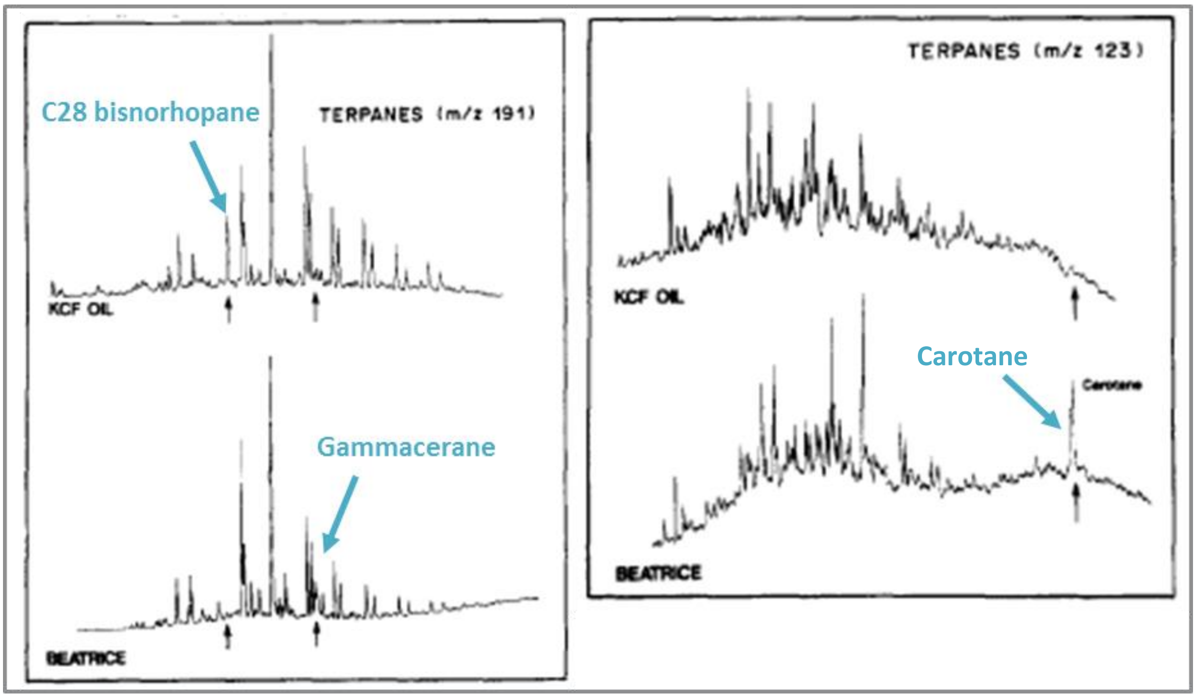

Figure 8: Comparison of GC-MS (m/z 191) and (m/z 123) for Beatrice oil and Kimmeridge Clay-sourced oil (adapted from Bailey et al., 1990), reproduced with permission of Elsevier.

4 Perceived Risks for Devonian-sourced plays

The main perceived risks for Devonian-sourced plays from the literature are:

- **Source rock distribution** – the presence and quality of the Middle Devonian source rock to the east is poorly constrained and the presence of Lower Devonian source rock is localised within half-grabens.
- **Timing of hydrocarbon generation and expulsion** – Late Palaeozoic timing for the generation and expulsion of hydrocarbons from Devonian source rocks is predicted for the onshore region; offshore the complex tectonic history has given rise to significant variations in maturity.
- **Migration** – Local source likely required as long-range migration is limited by significant faulting, high wax-content of Devonian oils and high degree of cementation within interbedded Devonian sandstones

4.1 SOURCE ROCK DISTRIBUTION

The overall extent of the Orcadian Lake in the Devonian is not well constrained, and the occurrence of good source rock potential within that extent is difficult to predict (Robertson Research International, 2001; Cornford, 2009). However, as was discussed in Section 2, the Devonian does outcrop at several locations around the edge of the Moray Firth Basin and has been proven in several offshore Quadrants: - Quads 11, 12, and 13 (Figure 1). The development of half-grabens during the early phase of rifting in the Orcadian Basin means the thickness of (particularly Lower) Devonian source rock could vary significantly across the basin, especially within different half-graben systems (Marshall et al., 1985; Curran, 1987a; Marshall & Hewett, 2003).

Lacustrine depositional environments can generate source facies which are regionally discontinuous in space and time, so it is reasonable to assume that good Devonian source rock is potentially more widespread in the Inner Moray Firth than present data suggests (The Geochem Group, 1986). For example, just outside of the study area, a Middle Devonian lacustrine sequence was encountered in well 9/16- 3, providing evidence for the extension of the Orcadian Basin into the Northern North Sea (Duncan & Buxton, 1995). The maximum TOC recorded in this well was 0.91% and HI was 498 (Duncan & Buxton, 1995) indicating a very poor oil-prone source rock (but with good organic matter preservation), albeit significantly lower quality than those source rocks within the Orcadian Basin depocentre. The samples from well 14/20b- 19 and 15/13- 2 which contained carotane are both unique in their quadrants (Robertson Research International, 2001), suggesting the Devonian source development could be quite limited in that area. Pedersen et al. (2006) proposed that the Devonian lacustrine-evaporitic system extended from the Orcadian Basin to offshore Norway, based on the presence of Devonian mudstones in the Norwegian well 15/5- 3.

4.2 TIMING OF HYDROCARBON GENERATION AND EXPULSION

Several basin modelling studies of the Orcadian Basin give an insight into the possible timing for hydrocarbon generation and migration in the region (e.g. Curran, 1987b; Keeley et al., 1990; Robertson Research International, 2001; Halliburton Geo Consultants, 1990). Onshore, the presence of Middle Devonian volcanics indicates high geothermal gradients in the Devonian (Astin, 1990); the Middle Devonian is thought to have achieved mid-late maturity across much of the region in the Late Palaeozoic (e.g. Parkinson, 1983; Curran, 1987b, Keeley et al., 1990; Trewin, 1989). This is supported by Apatite Fission Track (AFTA) data which indicate maximum burial depth and temperatures for the Devonian outcrops were experienced in the Devonian, Carboniferous and possibly into the Permian (Robertson Research International, 2001). 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, faulting and deep erosion during the Permian inversion episode (Curran, 1987b; Marshall, 1998; Trewin, 1989). 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).

However, Mesozoic aged generation is supported by the presence of Devonian-sourced oil in well 12/27- 1 (Curran, 1987b) where the most recent phase of hydrocarbon generation within the Devonian interval is thought to have occurred during maximum burial in the Tertiary (Marshall, 1998). Relatively recent generation of the Beatrice oil has been inferred due to the high wax content of the oil which would have cracked through to gas if subjected to elevated temperatures and pressures for a considerable length of time (Hogan et al., 1978). 2D basin modelling over the presumed kitchen for the Beatrice Field indicates the Devonian entered the oil window in the Early Cretaceous, with gas generation from the Late Cretaceous (Robertson Research International, 2001). Hydrocarbon generation ended in the Eocene due to inversion, although migration continued through to the Late Tertiary (Robertson Research International, 2001).

4.3 MIGRATION

Underhill (1991) invoked long distance migration (over 20 km) to charge the Beatrice structure, from a kitchen in the northern part of the Sutherland Terrace where maximum Mesozoic burial of the Devonian and Jurassic source rocks occurred. However, for major oil accumulations in the west of the Inner Moray Firth, long-range lateral migration from the Kimmeridge Clay Formation kitchen (at the Halibut Horst, Witch Ground Graben and Buchan Graben) is unlikely due to significant faulting within the Jurassic and Lower Cretaceous fairway, so these fields must be sourced by a local Devonian or Middle Jurassic source rock, with the Devonian being the only candidate for sourcing any hydrocarbon (Hogan et al, 1978; The Geochem Group, 1986). Further, long-range migration would be hindered as waxy oil (as found at the Beatrice Field) exhibits limited mobility under the existing subsurface conditions (Hogan et al, 1978). In the East Orkney Basin, the Devonian sandstones generally have very poor reservoir properties due to high degrees of diagenetic quartz cementation and the presence of clay minerals so the possibility of an interbedded Devonian source/reservoir play in this area is limited (Edrich, 1980). Production could, however, be enhanced in the presence of fractures as at the Buchan and Argyll fields (Marshall & Hewett, 2003).

5 Conclusions

- Outcrop and well data indicate the presence of good quality, variably mature Lower-Middle Devonian lacustrine source rock in the Orcadian Basin, although the eastward extent of the play is poorly constrained.
- 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.
- Timing of maturity and migration is locally variable but key to understanding the potential of any Devonian-sourced play.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

ASTIN, T.R. 1990. The Devonian lacustrine sediments of Orkney, Scotland; implications for climate cyclicity, basin structure and maturation history, *Journal of the Geological Society, London,* Vol 147, 141-151.

BAILEY, N.J.L., BURWOOD, R. AND HARRIMAN, G.E. 1990. Application of pyrolysate carbon isotope and biomarker technology to organofacies definition and oil correlation problems in North Sea basins. *Organic Geochemistry,* Vol. 16, Nos 4-6, 1157-1172.

CORNFORD, C., 2009. Source Rocks and Hydrocarbons of the North Sea. *Petroleum Geology of the North Sea: Basic Concepts and Recent Advances: Fourth Edition*, 376-462.

COWARD, R. N., CLARK, N. M. AND PINNOCK, S. J., 1991. The Tartan Field, Block 15/16, UK North Sea. *Geological Society, London*, Memoirs Vol. 14, 377-384.

CURRAN, P.M. 1987a. A Geochemical Study of the Inner Moray Firth, Quadrants 11-13, UKCS, *BP Petroleum Development Ltd* Report EX/AB/5221. Proprietary report, in confidence to Palaeozoic project.

CURRAN, P.M.1987b. Timing of Hydrocarbon Generation and Volumes of Oil Generated in the Inner Moray Firth. *BP Technical File note TFN/668*. Proprietary report, in confidence to Palaeozoic project.

CURRAN, P.M. & FISCHER, M.W. 1987. The Geochemistry of Outcrop Samples from the Brora-Helmsdale Area, and of Core and Cuttings Samples from Wells 11/30-1, 12/21-2 and 12/21-3 *BP Report GL/AB/2335*. Proprietary report, in confidence to Palaeozoic project.

DUNCAN, A.D., AND HAMILTON, R.F.M. . 1988. Palaeolimnology and organic geochemistry of the Middle Devonian in the Orcadian Basin pp 173-201. in *Lacustrine Petroleum Source Rocks*. FLEET, A.J., KELTS, K., and Talbot, M.R. (editors). (Geological Society Special Publication No 40)

DUNCAN, W. I. AND BUXTON, N. W. K. 1995. New evidence for evaporitic Middle Devonian lacustrine sediments with hydrocarbon source potential on the East Shetland Platform, North Sea. *Journal of the Geological Society, London*, Vol. 152, 251-258.

EDRICH, S.P., 1980. A Geological Appraisal of Prospects in the East Orkney Basin. *BP Petroleum Development Ltd UK Exploration and Production Report GL/AB/997.* Proprietary report, in confidence to Palaeozoic project.

EDWARDS, C.W., 1991. The Buchan Field, Blocks 20/5a and 21/1a, UK North Sea. In Abbots, I.L. (ed). *United Kingdom Oil and Gas Fields, 25 Years Commemorative Volume,* Geological Society Memoir No. 14, 253-259

HALLIBURTON GEO CONSULTANTS, 1990. An Integrated Geophysical and Geological Evaluation of Play Types in the Moray Firth. *Non-exclusive Hydrocarbon Exploration Study*.

HARKER, S. D., GREEN, S.C.H., AND ROMANI, R. S. 1991. The Claymore Field, Block 14/19, UK North Sea. *Geological Society, London*, Memoirs Vol. 14, 269-278.

HEWETT, T. 1993. 12/29-2 – A Complete Devonian Sequence Penetrated Offshore. Framework of the Orcadian Basin Geology Conference Abstract.

HILLIER, S., AND MARSHALL, J.E.A. 1992. Organic maturation, thermal history and ydrocarbon generation in the Orcadian Basin, Scotland. *Journal of the Geological Society, London*, Vol. 149, 491–502.

HOGAN, J.A., JONES, T.P. AND MILLS, S.J. 1978. Evaluation of the Beatrice Field and reappraisal of the Inner Moray Firth Basin. *British National Oil Corporation.* Donated by BP for Palaeozoic project.

KEELEY, M., STAFFORD, J., BRAY, R., STALKER, T., MILES, W. AND HORSCROFT, R. 1990. The Moray Firth, A Basin Modelling Stdy Volume 2. *ECL Petroleum Technologies.* Donated by BP for Palaeozoic project.

MACKENZIE, A.S., MAXWELL, J.R., COLEMAN, M.L. AND DEEGAN, C.E. 1984. Biological Marker and Isotope Studies of North Sea Crude Oils and Sediments. *Proceedings of the 11th World Petroleum Congress*, Vol. 5, 45-56.

MARSHALL, J.E.A. 1998. The recognition of multiple hydrocarbon generation episodes: an example from Devonian lacustrine sedimentary rocks in the Inner Moray Firth, Scotland. *Journal of the Geological Society, London*, Vol. 155, 335-352.

MARSHALL, J.E.A., BROWN, J.F. AND HINDMARSH, S. 1985. Hydrocarbon source rock potential of the Devonian source rocks of the Orcadian Basin. *Scottish Journal of Geology,* Vol. 21 (3), 301-320.

MARSHALL, J. E. A. AND HEWETT, A. J, 2003. Devonian 65-81 in *The Millenium Atlas: petroleum geology of the central and northern North Sea*. EVANS, D., GRAHAM, C., ARMOUR, A. and BATHURST, P. (editors and co-ordinators)., The Geological Society of London, PESGB edition.

PARKINSON, D. N. 1983. The Old Red Sandstone of the Orcadian Basin as a Hydrocarbon Source and an Exploration Play. *GL/AB/1514*. Proprietary report, in confidence to Palaeozoic project.

PEDERSEN, J. H., KARLSEN, D. A., LIE, J.E., BRUNSTAD, H.,AND DI PRIMIO, R, 2006. Maturity and source-rock potential of Palaeozoic sediments in the NW European Northern Permian Basin. *Petroleum Geoscience*, Vol. 12, 13-28.

PETERS, K. E., CLUTSON, M. J., AND ROBERTSON, G 1999. Mixed marine and lacustrine input to an oil-cemented sandstone breccia from Brora, Scotland. *Organic Geochemistry*, Vol. 30, 237-248.

PETERS, K. E., MOLDOWAN, J., DRISCOLE, A. AND DEMAISON, G. J. H. 1989. Origin of Beatrice oil by co-sourcing from Devonian and Middle Jurassic source rocks, Inner Moray Firth, UK. *Bulletin of the American Association of Petroleum Geologists,* Vol. 73, 454-471.

PETERS, K. E., WALTERS, C. C., AND MOLDOWAN, J. M. 2005. The Biomarker Guide. *Cambridge University Press*.

ROBERTSON RESEARCH INTERNATIONAL. 2001. Moray Firth Basins, Hydrocarbon Provenance and Modelling Vol 1.Used with permission from CGG.

SCHMITT, H.R. AND GORDON, A. F., 1991. The Piper Field, Block 15/17, UK North Sea. *Geological Society, London*, Memoirs Vol. 14, 361-368.

STEVENS, V., 1991. The Beatrice Field, Block 11/30a, UK North Sea. *Geological Society, London*, Memoirs Vol. 14, 245-252.

THE GEOCHEM GROUP, 1986. A regional geochemical and oil correlation study of the Inner Moray Firth. Donated by BP for Palaeozoic project.

TREWIN, N.H. 1989. The petroleum potential of the Old Red Sandstone of northern Scotland. *Scottish Journal of Geology,* Vol. 25 (2) p201-225.

UNDERHILL, J R. 1991. Implications of Mesozoic-Recent basin development in the western Inner Moray Firth, UK. *Marine and Petroleum Geology,* Vol. 8,.

VANE C H, UGANA C, KIM A W, MONAGHAN A A. 2016. Organic Geochemistry of Palaeozoic Source Rocks, Orcadian Study Area, North Sea, UK. British Geological Survey Commissioned Report, CR/16/037. 41pp.

WESTON, J.R. AND WINSTANLEY, A.M. 1983. A Review of the East Orkney Basin. *BP Petroleum Development Ltd Exploration and Production Report EX/AB/5107*. Proprietary report, in confidence to Palaeozoic project.

WHITEHEAD, M. AND PINNOCK, S. J., 1991. The Highlander Field, Block 14/20b, UK North Sea. *Geological Society, London*, Memoirs Vol. 14, 323-329.