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Palaeozoic Petroleum Systems of the Irish Sea

Energy and Marine Geoscience Programme

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BRITISH GEOLOGICAL SURVEY

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COMMISSIONED REPORT CR/16/045

Palaeozoic Petroleum Systems of the Irish Sea

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Front cover

Saltom Bay, Cumberland. View looking south-west towards the Isle of Man along the submerged Ramsey-Whitehaven Ridge. Photo: Tim Pharaoh

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

Foreword and acknowledgements

This report is a published product of the 21st Century Exploration Roadmap (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. Centrica are thanked for donation of 3D seismic data. Seismic companies (CGG, IHS Global Limited, WesternGeco/Schlumberger) are thanked for allowing reproduction of selected regional seismic lines and for agreeing to the release of a set of 5 km resolution grids. Seismic interpretations for some post-Permian interpretations in the East Irish Sea were provided by agreement from the CO_2Stored Project. The assistance of John Williams in loading and quality controlling well data in the workstation environment is gratefully acknowledged.

Jim Ritchie (LR Senergy), Colin Tiltman and Myles Taylor (Centrica) are thanked for technical review of this report and associated digital data.

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Summary

This report synthesises the results of the 21CXRM Palaeozoic project in the Irish Sea to describe the Palaeozoic petroleum systems of that area.

One hydrocarbon play system dominates the basin system: Namurian organic-rich marine shales (Bowland Shale Formation) generated oil and gas with a peak during maximum burial of the system in late Jurassic/early Cretaceous time. These hydrocarbons passed to reservoirs in the Triassic Ormskirk Sandstone (Sherwood Sandstone Group) by way of structures generated during the Variscan Orogeny and Cenozoic inversion, resulting in the Morecambe, Hamilton and other gas and oil fields

The Palaeozoic study of the wider Irish Sea area has assessed the potential for more widespread petroleum systems situated outside the well-known play, particularly within the Carboniferous.

Within the Main Graben system of the East Irish Sea Basin, Coal Measures strata were partially removed following Variscan inversion and early Permian uplift. They are not rich in coals, and not inferred to be a significant source rock. There is some potential in the Millstone Grit and Yoredale sequences, as some shales (particularly those associated with marine bands) are known to have high Total Organic Contents. The source rock potential of shales within the Carboniferous Limestone sequence is poorly constrained by data. A Devonian source rock is unproven and considered unlikely.

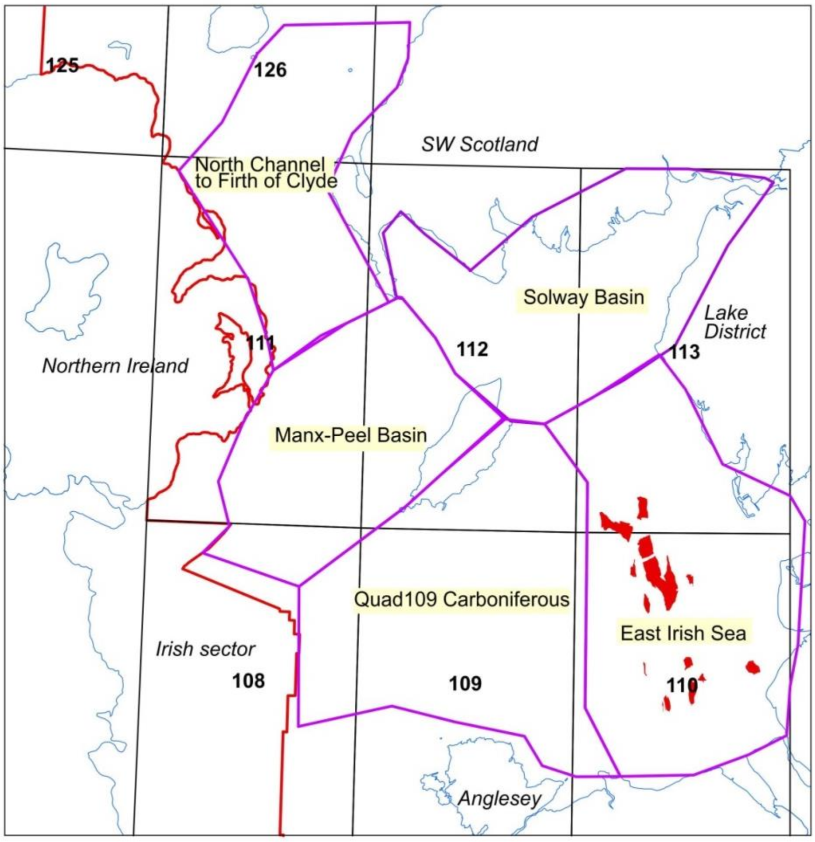
Potential Namurian source rocks, such as the Yoredale Group, have been largely eroded in the Peel and North Channel basins, considerably reducing their prospectivity, although terrestrial sequences of equivalent age in the Solway Basin may offer better potential.

The variable seismic data quality at Carboniferous levels and sparsity of deep well control have led to challenges in interpretation, particularly of the deeper picks. The interpretation of the surfaces contains a strong model-driven element, evidenced by the onshore relationships and areas where seismic picks can be made with the greatest confidence. Based upon the integration of regional seismic mapping with a limited well, source rock and reservoir property dataset, the most prospective parts of the region, outside the Ormskirk conventional gas play, are considered to be:

- The thick Westphalian sequences preserved in the Eubonia Tilt-Block in Quadrant 109, outside the main Permian-Mesozoic graben system and unaffected by Cenozoic inversion. The presence and quality of seals form a major risk as the Cumbrian Coast Group seal is thin or absent and Carboniferous intraformational seals are required but untested. Based on the limited dataset available in adjacent basins, reservoir quality is also a significant risk.
- A belt of Variscan inversion structures correlated with structures on the Formby Platform, and Ribbledale Foldbelt onshore, from which hydrocarbons have leaked into the overlying, Ormskirk-hosted Hamilton fields. The biggest risk here is whether reservoirs remain unbreached at the Pre-Permian level, and retain good poroperm characteristics at depths of about 2500 m.
- A more speculative play lies in the extensive carbonate platform in Quadrant 109 and surrounding the Isle of Man, in reefal facies with enhanced secondary porosity. Here, source rock presence and migration pathways, reservoir properties and seal quality are major risks.

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 Irish Sea study area (Figure 1). It does not include the Celtic Sea.



Focus of tasks
A. Regional structure, tectonics, stratigraphy with petroleum system focus including onshore links
B. Reservoir quality in Carboniferous (and Permian)
C. Source rock distribution, quality e.g. extent of Bowland Shale etc

Figure 1 Focus of tasks in the Irish Sea Study

The main focus of study across the Irish Sea area (Figure 1) was to undertake regional mapping of basin structure and stratigraphy, particularly of Carboniferous sequences (see Pharaoh et al. 2016a). A regional scale examination of reservoir quality (Hannis, 2016) and an improved understanding of likely source rock distribution and quality (Wakefield et al., 2016, Vane et al., 2016) and maturation history (Gent, 2016) were also undertaken.

Onshore, adjacent to the eastern margin of the Irish Sea, a working Carboniferous petroleum system has been exploited for many years. The Carboniferous-sourced, Triassic-reservoired Formby Oilfield onshore was discovered in 1939, with seeps into Quaternary sands .The giant Morecambe Field was discovered in 1974, with satellite fields proved up through the 1980's and 1990's. In 1990, gas was discovered in the Elswick field onshore, and soon after, oil and gas in the Hamilton, Douglas and Lennox fields offshore. Offshore, further gas discoveries continue to the present day (e.g. Rhyl in 2009) while onshore, focus has switched to the exploration for unconventional, shale-gas resources in the Bowland Shale Formation, with wells at Preese Hall and elsewhere (Cuadrilla, 2015). In addition, farther east, the East Midlands oil fields are largely sourced from Namurian basinal shales (Pletsch et al., 2010), are reservoired in Namurian and Westphalian channel sandstones, and have been producing at flat rates for many years.

2 Data used in study

2.1 PUBLISHED INFORMATION

The project commenced with a review of the extensive published literature of the Irish Sea and adjacent land areas. The region was the focus of a major offshore mapping programme using analog seismic data in the 1980's and early 1990's. The results of this work (BGS, 1994; Jackson et al., 1995) were used extensively in the present study. In the early 1990's numerous reports were produced as part of the NIREX waste repository investigations, offshore Sellafield. These studies, including interpretation of available analog seismic data, were encapsulated in various reports on the 'district' and 'regional'scales (Figure 2). Another significant milestone was the publication of the 'Isle of Man Memoir', which provided extensive information on the geology of the offshore area (Chadwick et al., 2001). A geological interpretation of the Larne and Portpatrick sub-basins was the subject of an unpublished report by Quinn (2008).

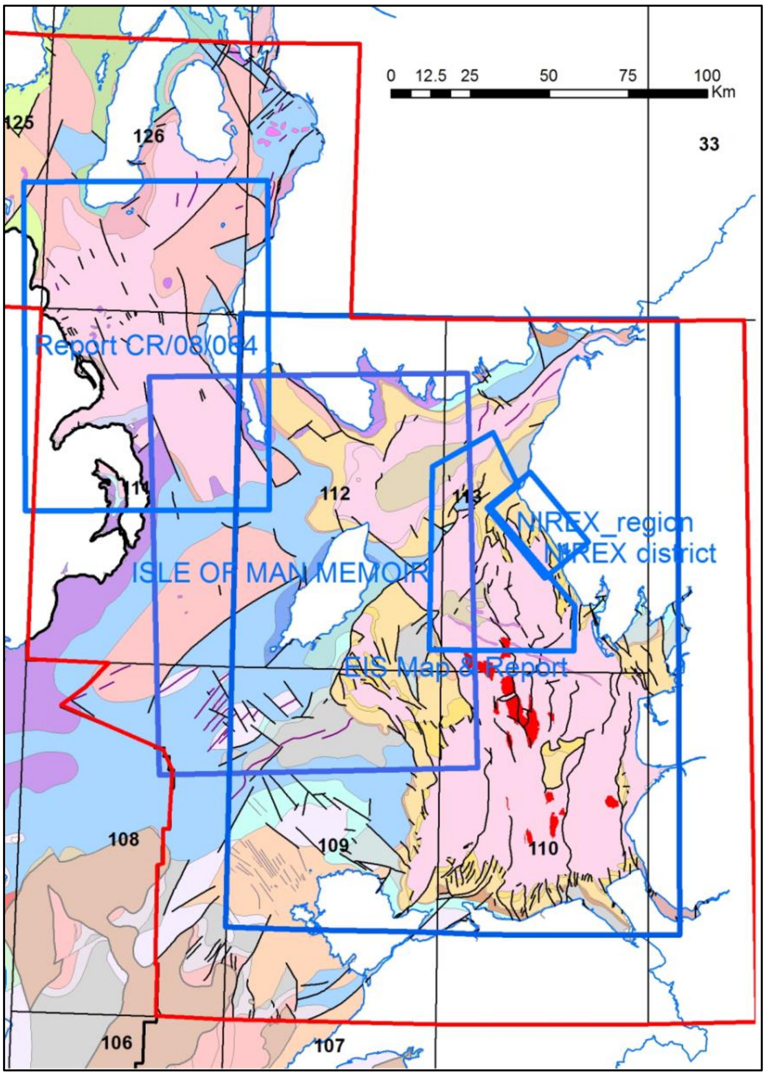


Figure 2 Geographical coverage of previous work incorporated into this report. Background bedrock geology from BGS 1:250,000 offshore DigMap BGS©NERC (Jurassic-Triassic in pink-browns, Carboniferous in grey and blue).

A large number of papers on the petroleum geology and tectonics of the Irish Sea were published in special publications of the Geological Society (Meadows et al., 1997; Woodcock et al., 1999). Numerous papers on the petroleum system were also published in the proceedings of the Petroleum Geology of NW Europe conferences, particularly Parker (1993).

<table>
<tr><th>Chronostratigraphy</th><th colspan="2">Current lithostratigraphic name</th><th>Former lithostratigraphic name[1]</th></tr>
<tr><td>Upper Permian</td><td colspan="2">Cumbrian Coast Group</td><td>Cumbrian Coast Group (includes St Bees Shales & Manchester Marls)</td></tr>
<tr><td>Middle Permian</td><td colspan="2">Appleby Group</td><td>Appleby Group (includes Collyhurst Sandstone & Manchester Marls)</td></tr>
<tr><td>Stephanian</td><td colspan="2" rowspan="2">Warwickshire Group</td><td rowspan="3">Kidston Group</td></tr>
<tr><td rowspan="2">Westphalian</td></tr>
<tr><td colspan="2">Pennine Coal Measures Group</td></tr>
<tr><td rowspan="2">Namurian</td><td colspan="2">Millstone Grit Group</td><td rowspan="2">Bisat Group</td></tr>
<tr><td rowspan="2">Yoredale Group</td><td rowspan="2">Craven Group</td></tr>
<tr><td rowspan="2">Visean</td><td rowspan="3">Garwood Group</td></tr>
<tr><td>Border Group</td><td rowspan="2">Carboniferous Limestone Supergroup</td></tr>
<tr><td>Tournaisian</td><td>Inverclyde/Raven-stonedale groups</td></tr>
</table>

Figure 3 Lithostratigraphical terminology used in this report compared with former nomenclature; 1 See: Jackson and Johnson (1996).

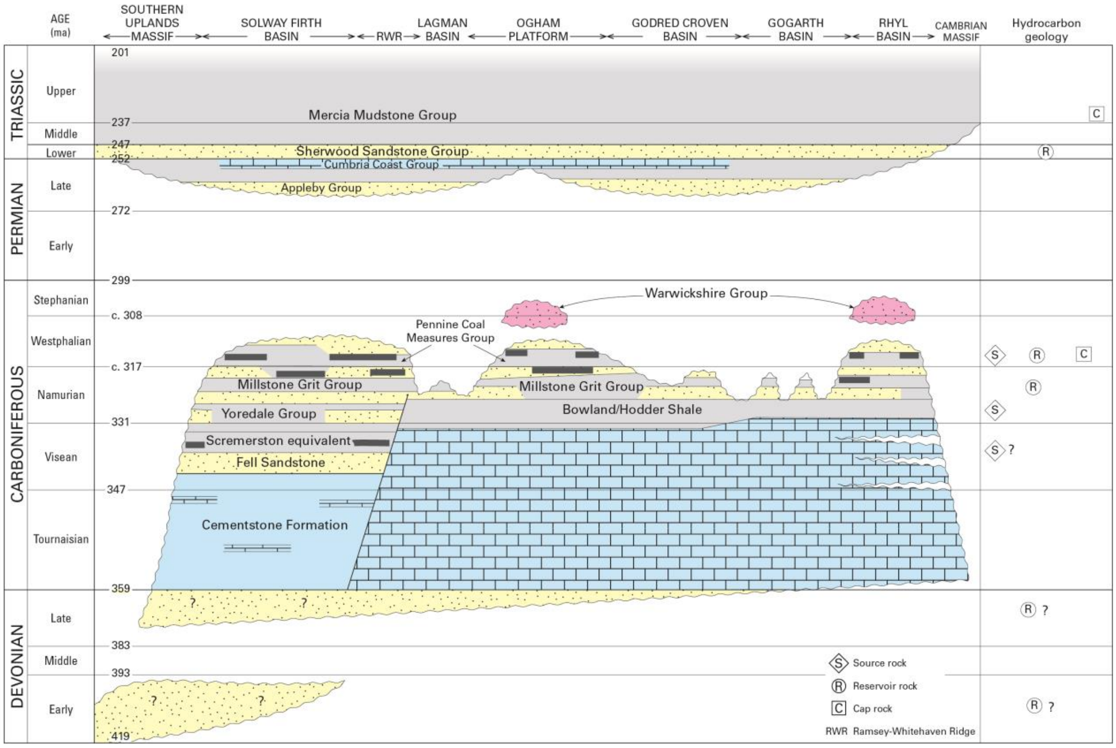


Figure 4 Synoptic diagram of the hydrocarbon systems of the Irish Sea basins, showing the principal source rocks, reservoirs and seals.

Figure 4 provides an overview of the principal elements of the hydrocarbon system in the Irish Sea basins, south of the Southern Upland Massif (the stratigraphical terminology used, and previous nomenclature are summarised in Figure 3). The Bowland Shale Formation is the principal source rock, with Westphalian coals and other Namurian/late Visean shales also possibly contributing. In the Solway Basin, the Scremerston Coal Formation and Yoredale Formation may contribute. Potential reservoirs are in Namurian and Westphalian sandstones which have not suffered strong Permian to Mesozoic burial and subsequent Cenozoic inversion. The reservoir potential of the extensive Carboniferous carbonate platform requires further investigation. Local absence of the Cumbrian Coast Group (Permian) and Mercia Mudstone Group (Triassic) seals/caprocks places heavy emphasis on the role of Carboniferous intra-formational seals.

2.2 SEISMIC DATA

Several thousand 2D reflection lines have been acquired in the region since the late 1960's, and include both relatively short exploration company data focussed on individual prospects, and regional seismic lines acquired by geophysical contractors on a speculative basis. For the former, a very limited number of lines were acquired from the CDA archive, with the remainder from the DECC data store at BGS in Edinburgh. Use of the regional lines is by agreement with the geophysical contractors, specifically CGG, IHS and Western Geco, subject to release of interpretations as 5 km resolution grids. Since the 1990's, 3D data have also become available as key players in the basin have focussed on the production characteristics of their producing assets. The functionality of these data has been greatly enhanced by CGG, in their TerraCube**REGRID** product. The assistance of these companies in providing data and permission for its use in the project is gratefully acknowledged.

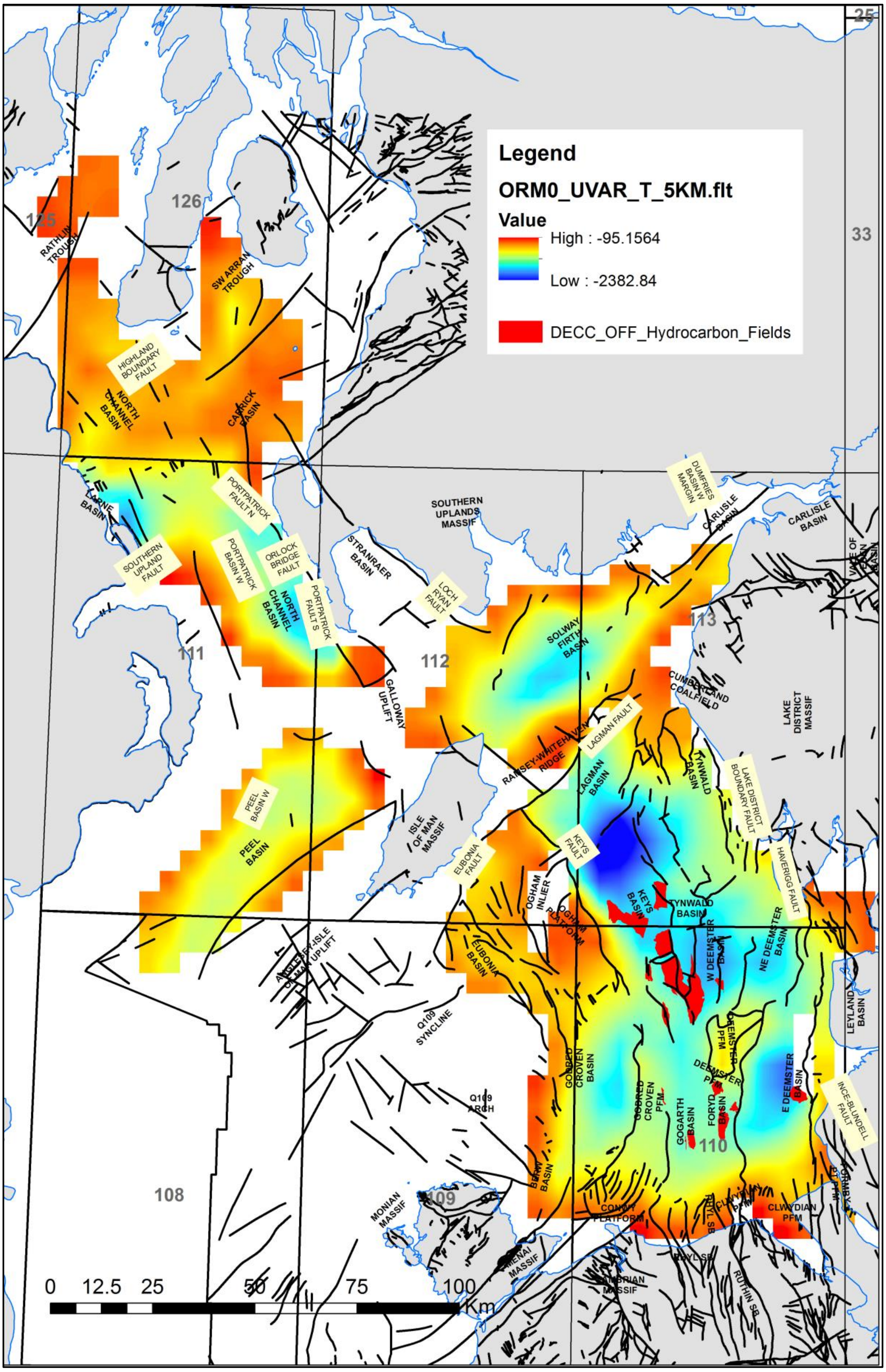


Figure 5 Structural terminology used in this report, following Jackson and Mullholland (1997). Structure map is the base Permian Unconformity in TWTT ms (see Pharaoh et al., 2016a). DECC hydrocarbon fields shown in red. The 'Main Graben' of the EISB referred to in the text is within the blue areas, the 'Marginal' graben/areas are green to red.

Figure. 6 illustrates a subset of the seismic data examined in the project. A more complete summary would be illegible due to the very high data density in the East Irish Sea Basin. Figure 6 does not include exploration company data in the Peel, Solway and North Channel basins. The coverage of the CGG TerraCube^{REGRID} data is shown in orange. With the limited resources available, attention was focussed on regional lines with best resolution of the Carboniferous sequence. Further details of the seismic interpretation project and its results are described in Pharaoh et al. (2016a), which specifies the data used.

It is important to note that the variable data quality and sparsity of deep wells leads to a seismic interpretation which is strongly driven by regional geological models, themselves heavily dependent on inference from the onshore area. This is particularly the case with the deeper Carboniferous horizons which are not penetrated by any well and which may be only weakly reflective. In such cases, picks from better quality data may be interpolated through areas with poor quality data, as a modelled surface, to ensure a continuous surface for gridding.

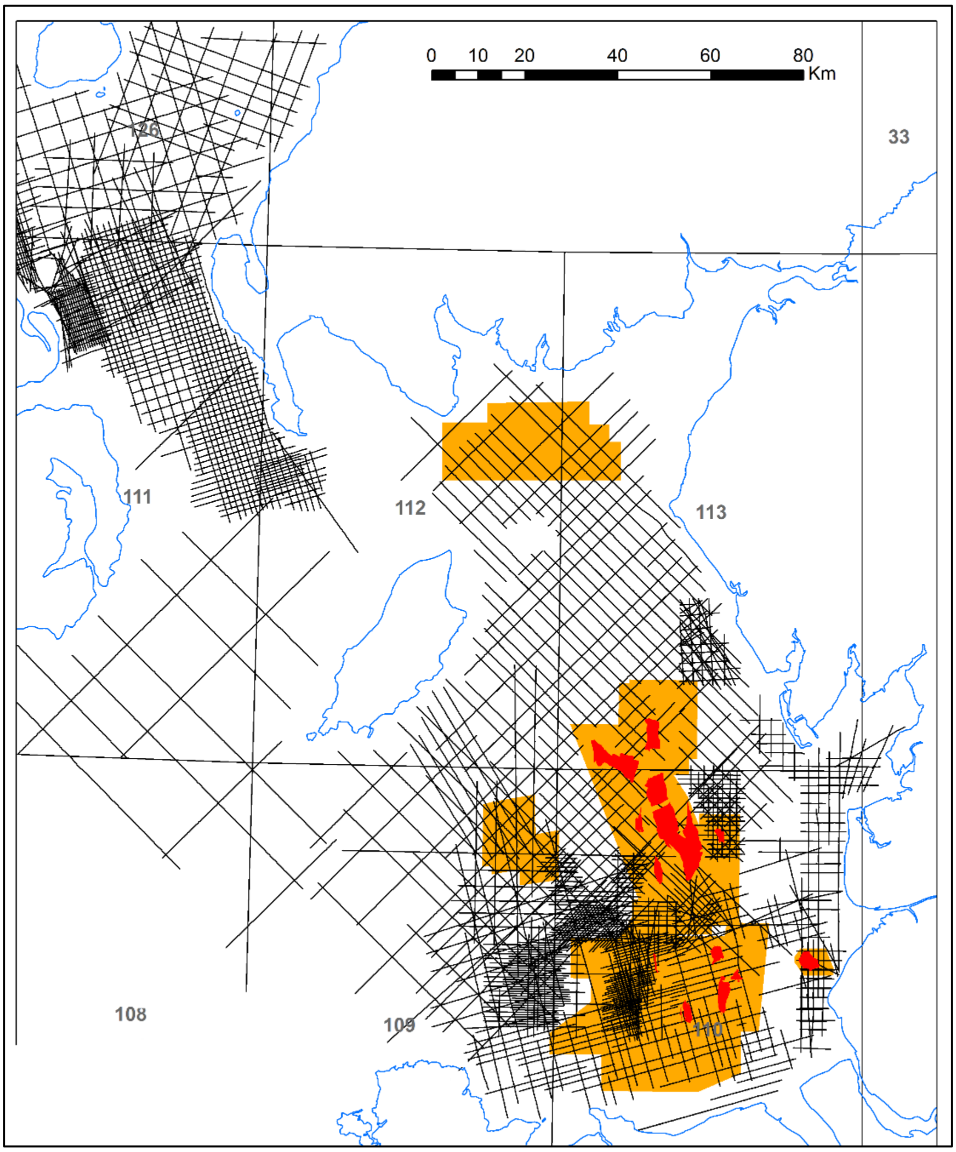


Figure 6 Regional speculative seismic data coverage in the region. Black, 2D reflection lines; Orange, ouline of CGG GeoSpec TerraCube^{REGRID} 3D coverage; Red, DECC offshore fields.

2.3 WELL INFORMATION

Some 30 wells penetrate the Permian and Carboniferous strata of the Irish Sea (Figure 7), Subsequent modification to the well tops in the composite log was carried out in the light of the seismic and stratigraphic investigations (Wakefield et al., 2016 and spreadsheet).

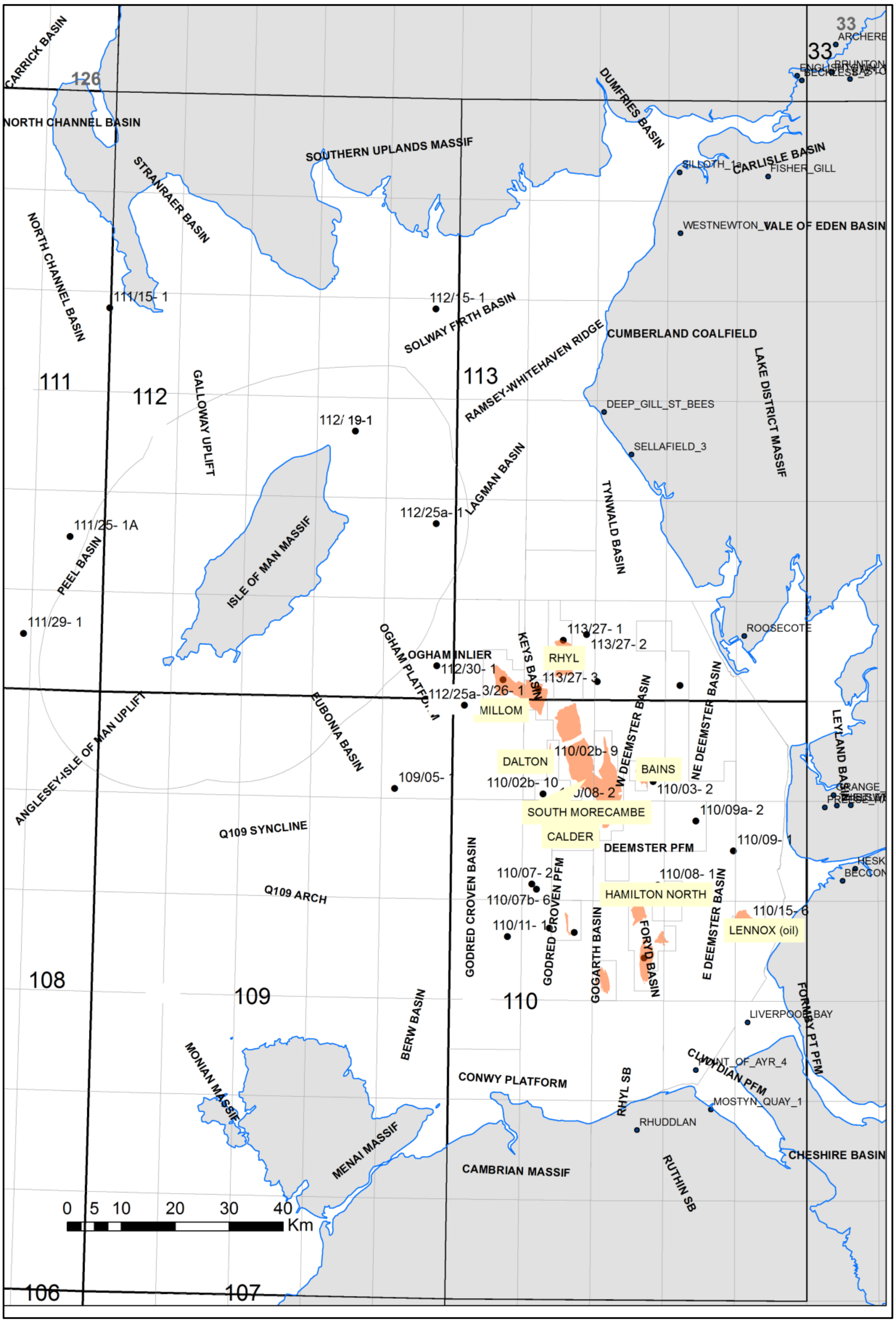


Figure 7 Key Carboniferous well penetrations, plus location of well 111/15- 1, and DECC offshore fields.

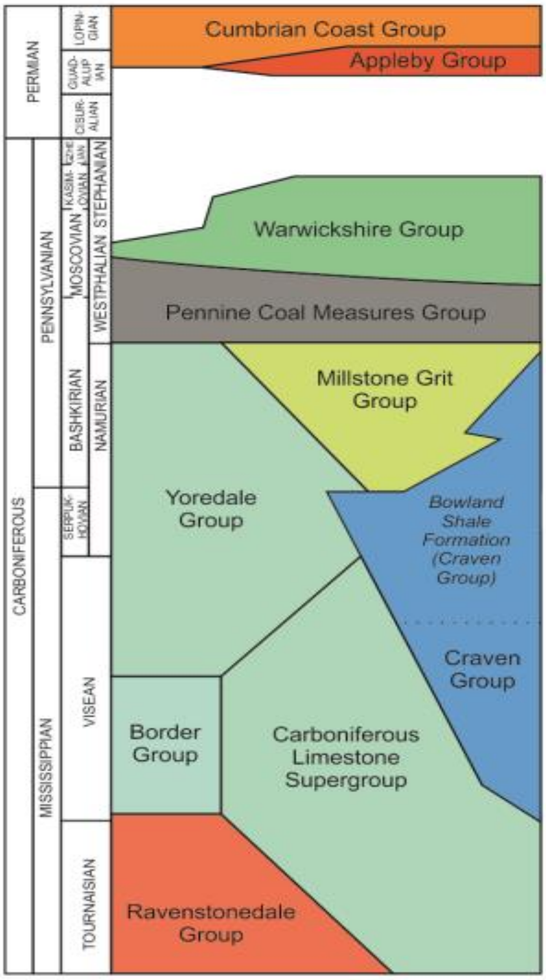


Figure 8 Major lithostratigraphic units in the study area (from Wakefield et al., 2016). North (Solway) is on the left hand side of the diagram; south (England and Wales) on the right hand side.

The relationship of the major lithostratigraphic units within the area is shown schematically in Figure 8. The diagram highlights the strong diachroneity inferred for some of the horizons mapped, in particular, the top of the Carboniferous Limestone Supergroup and overlying Craven Group, and the top of the Bowland Shale Formation with the overlying Millstone Grit Group. The equivalence of the Border and Yoredale groups in the north with the Carboniferous Limestone Supergroup in the south is also notable. The reader is referred to Wakefield et al. (2016) for further details. The seismic picks depicted in Figure 9 should be interpreted in this light.

Petrophysical interpretation from well geophysical logs is available and has been combined with available well core porosity and permeability data (Hannis, 2016).

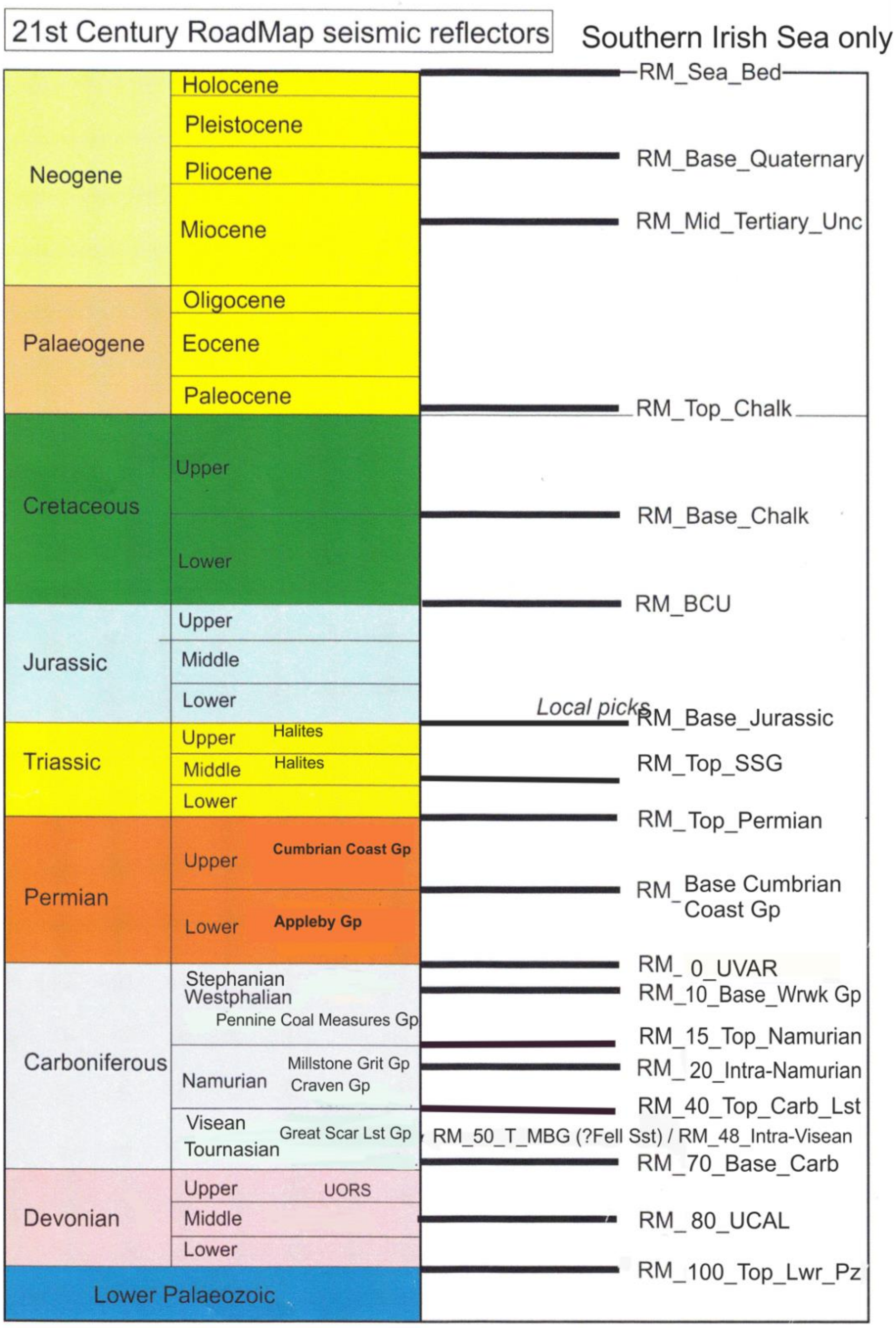


Figure 9 Seismic picks used in the project. See Pharaoh et al. (2016a) for further details.

2.4 ORGANIC GEOCHEMISTRY DATA

The limited organic geochemistry dataset available has been summarised by Vane et al (2016).

2.5 BASIN MODELLING DATA

A limited dataset of vitrinite reflectance and AFTA is available. These data have been used to constrain the basin modelling work presented by Gent (2016).

3 Potential field overview

Potential field (gravity and magnetic) data highlight the principal structural trends in the region, and allow extrapolation of those trends from the centre of the basin towards its margins, where the coverage of seismic reflection data is sparse. The magnetic data also image key features, such as the Cenozoic dyke swarms, with greater clarity than the seismic reflection data. Below is a brief review of the potential field data currently available to the study. No further modelling work was undertaken for this project.

3.1 MAGNETIC FIELD

The magnetic field (Figures 10, 11) provides evidence of both deep (intra-basement) and shallow magnetic structure. The deep effects include magnetic signatures associated with the Iapetus Suture Zone and the offshore extension of the Southern Borrowdales Lineament, as discussed by Kimbell and Stone (1995), Kimbell and Quirk (1999), Chadwick et al. (2001) and Kimbell et al. (2006). In those interpretations, the long-wavelength magnetic highs in the areas east and south of the Isle of Man were interpreted to be associated with Avalonian crystalline basement, while the magnetic low to the north of this belt was linked to a zone where metasedimentary rocks initially deposited at the margins of the Iapetus Ocean were carried to deeper crustal levels within the northward-dipping Iapetus Suture Zone. The mid-crustal magnetic rocks that underlie the Southern Uplands lie on the Laurentian side of the suture, but Kimbell and Stone (1995) argue that they might still have originated from the Avalonian (Gondwanan) side of the ocean and accreted to Laurentia prior to final closure (see also Armstrong and Owen, 2001; Philips et al., 2003). The distinct change in the trend of the long wavelength magnetic anomalies (from ENE in the east to NE in the west has been discussed by Kimbell and Quirk (1999) and Kimbell et al. (2006), who suggested that it was inherited from the grain of the Avalonian basement which includes features with both of these trends.

The possible offshore extension of the Southern Borrowdales Lineament lies along the south-eastern edge of the zone of Irish Sea long-wavelength magnetic anomalies, passing through the NW corner of Quadrant 110 and across the centre of Quadrant 109. Where exposed in the southern Lake District, this lineament is associated with a south-eastward-facing monocline interpreted by Kneller and Bell (1993) as an Acadian mountain front overlying a blind south-eastward vergent thrust and north-westward-directed back-thrusting. Their interpretation involved a south-eastward shallowing of magnetic basement across the lineament whereas the offshore signatures are indicative of a north-westward shallowing of the magnetic rocks. Regional imaging (e.g. Kimbell et al., 2006) indicates a discontinuity in magnetic trends across the lineament (including its north-eastward extrapolation along the southern side of the Alston Block) which may be indicative of a fundamental change in basement structure. In the onshore area this change appears to have influenced the geometry of the overlying Upper Palaeozoic basins, and there is evidence for a similar effect beneath the Irish Sea. The offshore lineament can be correlated with the southern end of the Ogham High and a change in the trends of the post-Acadian basins from broadly NW-SE to the north to N-S to the south.

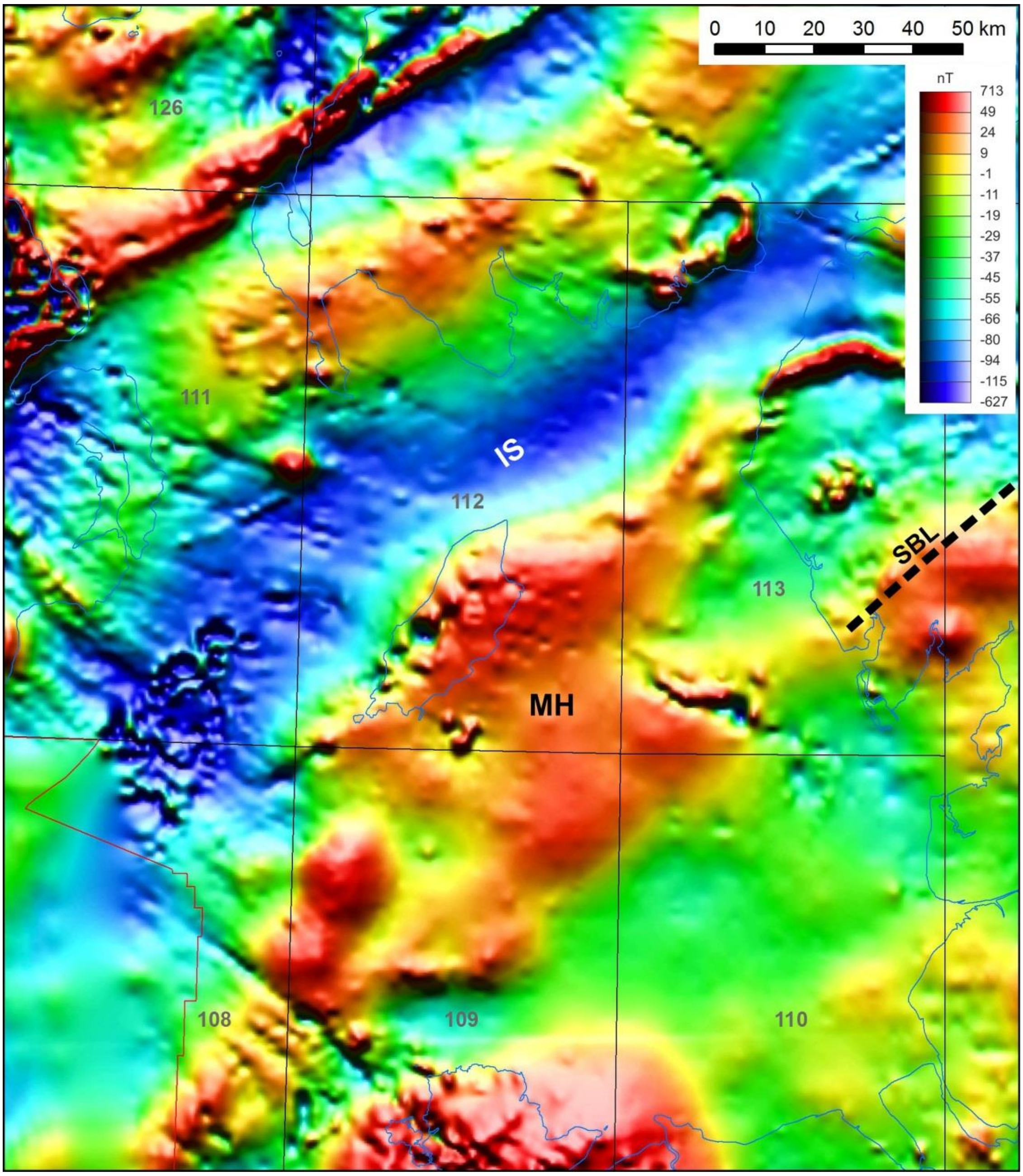


Figure 10 Reduced to pole magnetic field, based on BGS data, Illumination is from the north. Key: IS, magnetic low over Iapetus Suture Zone; SBL, Southern Borrowdales Lineament; MH, zone of relatively high magnetic field between IS and the offshore extrapolation of the SBL.

Shallow magnetic features in the area around the Isle of Man are well-imaged by the high-resolution aeromagnetic data reported by Chadwick et al. (2001). An image of the residual magnetic field is shown in Figure 11 and features identified from this are delineated in Figure 12. The original survey extended to the east of the area shown in these figures, and readers are referred to the data owners (Fugro Airborne Surveys) for further details of the available coverage. The survey resolves a complex pattern of generally SE-trending Palaeogene dykes, with normally and reversely magnetised examples indicated by linear magnetic highs and lows respectively (Figures 11 and 12). The reversely magnetised dykes which extend from Northern Ireland towards the Isle of Man can be correlated with the Ardglass-Ballycastle swarm in the former area, for which Cooper et al. (2012) suggested a Selandian age (chron

C26R). Where this swarm extends to the east of the Isle of Man it includes the prominent Fleetwood Dyke Complex (Kirton and Donato, 1985; Arter and Fagin, 1993). Normally magnetised dykes to the south of the Isle of Man may be part of the younger (Thanetian; C26N or C25N) St Johns-Lisburn swarm, and these may be interspersed with reversely magnetised dykes of an eastward extension of the older (Danian; C27R) Donegal-Kinscourt swarm (Cooper et al., 2012).

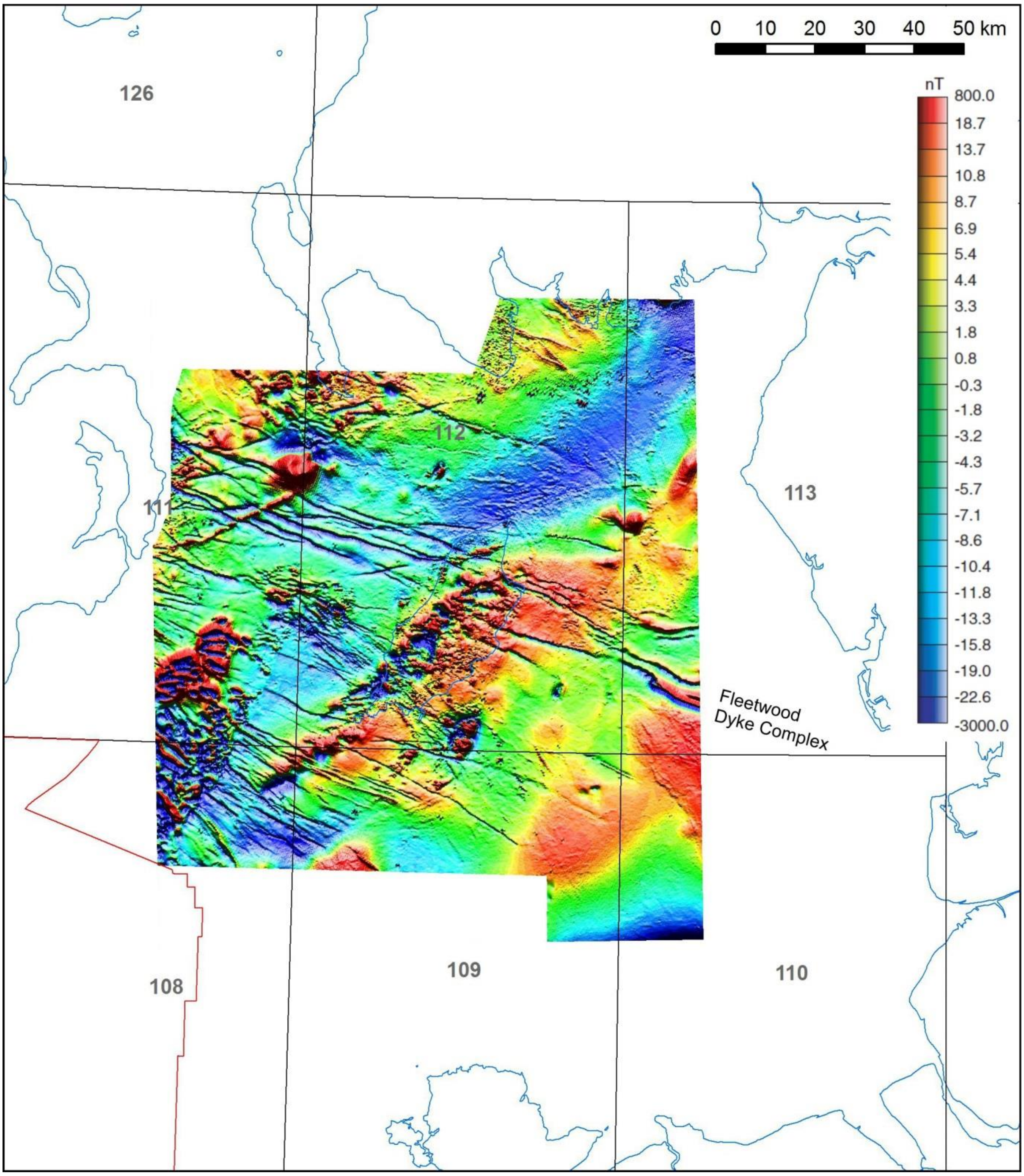


Figure 11 Residual total magnetic intensity over the Isle of Man area, calculated by removal of a 2 km upward continuation. Reproduced from Chadwick et al. (2001) and based on surveys flown by World Geoscience (UK) Ltd. (subsequently Fugro Airborne Surveys Ltd.). Illumination is from the north.

Zones of magnetic disturbance within the Peel and North Channel basins were interpreted by Chadwick et al. (2001) as the signatures of Palaeogene sills which formed preferentially along the bedding planes within these basins. A zone of shallow magnetic disturbance that crosses the Isle of Man in a SW-NE direction appears to be linked to the Caledonian Barrule Thrust Zone, which is imaged seismically in the offshore area (Chadwick et al., 2001, Figures 44 and 45 in Section 5 of this report). The strong reversed magnetisation within this zone indicated by the magnetic anomalies may be associated with secondary mineralisation or later intrusives (Chadwick et al., 2001). A local positive magnetic anomaly just south of the Isle of Man (at the centre of the southern edge of Quadrant 112) appears to lie in the immediate footwall of the Eubonia Fault and may be associated with a basement source or a local, normally magnetised Palaeogene intrusion.

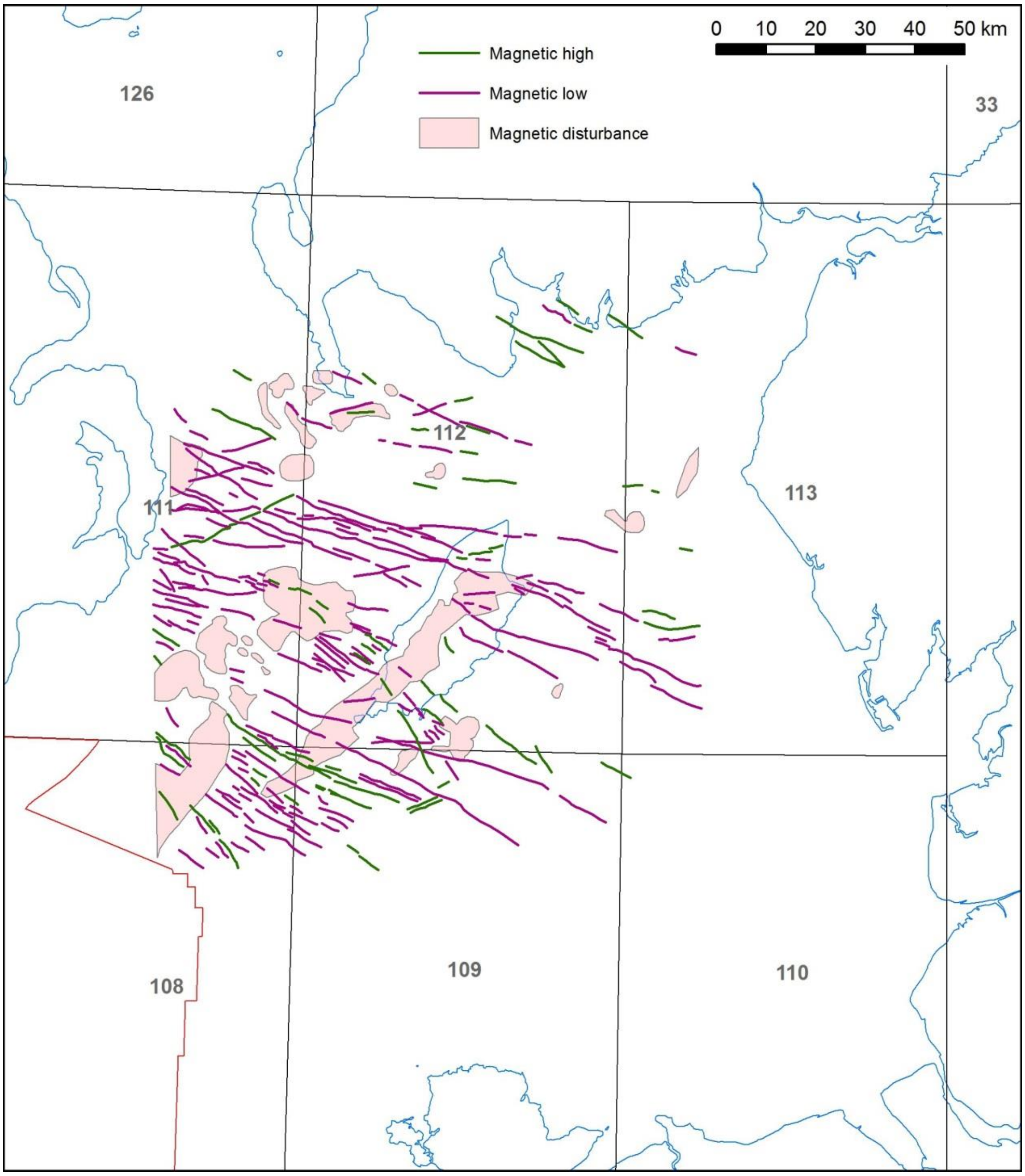


Figure 12 Summary figure, based on data shown in Figure 11, showing the anomalies identified from detailed aeromagnetic data in the vicinity of the Isle of Man and mainly associated with Palaeogene igneous features. From Chadwick et al. (2001).

3.2 GRAVITY FIELD

The main part of the composite gravity image shown in Figure 13 is from Kimbell et al. (2006). This published version is used because the data compilation it was based on incorporated non-BGS gravity data (from Western Geophysical and the Hydrographic Office, with permission from those data owners), with a substantial improvement in the quality of gravity imaging in the Irish Sea area. Comparison of structural mapping and gravity images indicates that the majority of gravity features in the offshore area coincide with variations in the thickness of the post-Variscan sedimentary rocks. Major faults affecting these rocks (e.g. the Lagman and Keys faults; cf. Figure 5) are well-resolved by strong gravity gradients. Although there is apparent continuity between gravity lows in the offshore and onshore (Lake District) areas, there is clearly a change in their cause, with the latter associated with the granite batholith that underpins that area. The gravity field over the onshore Southern Uplands includes lows due to both granites (Loch Doon, Cairnsmore of Fleet and Criffel) and Permo-Triassic basins (Stranraer, Dumfries and Thornhill). Local gravity lows on the Isle of Man are associated with the Foxdale Granite towards the south-west and (less conspicuously) the Dhoon Granite towards the north-east.

In general, it is difficult to assess the contribution of pre-Variscan sediment thickness variation to the gravity anomalies observed in the present study area without quantitative modelling (removal of the gravity effect of the younger sedimentary rocks). It does appear likely, however, that the gravity lows to the south and south-east of the Isle of Man contain a significant contribution from the pre-Variscan sequence. A relative gravity low is associated with the Quadrant 109 Basin where it extends beyond the western limit of the Permo-Triassic subcrop (Figures 13 and 14). The south-westward termination of this feature occurs against a block of shallower crystalline basement indicated by a magnetic high on the western side of Quadrant 109 (Figure 10). Future investigations could use this area to calibrate the gravity response of the pre-Variscan basin and the integrated modelling could be extended into the Eubonia Basin area to the north-east where it is overprinted by a post-Variscan contribution.

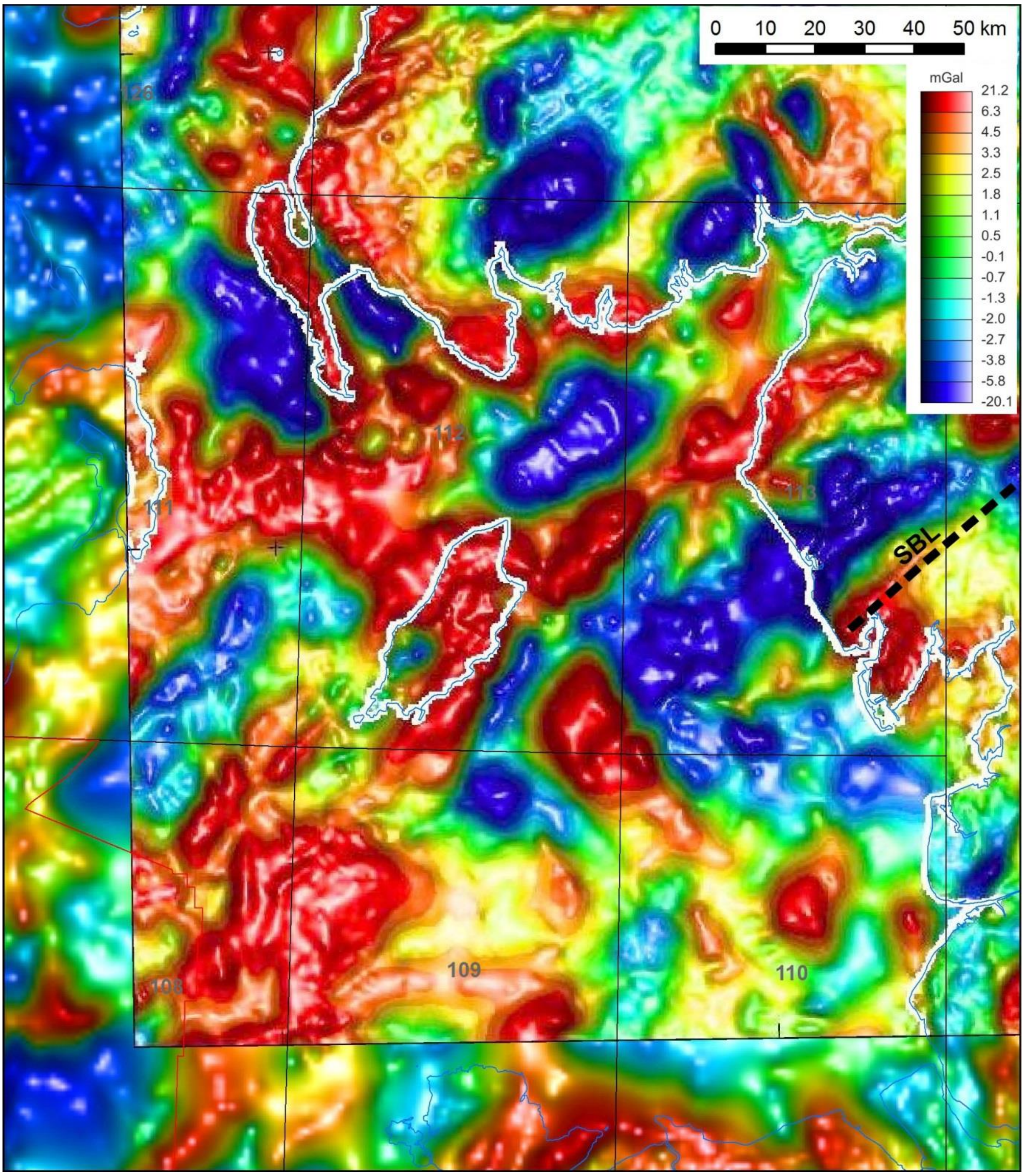


Figure 13 Composite residual Bouguer gravity anomaly image. The main (north-eastern) part is reproduced from Kimbell et al. (2006), who employed a gravity compilation based on data owned by BGS, Western Geophysical and the Hydrographic Office. The peripheral areas in the west and south are based on BGS data only. The residual was calculated by subtracting a 10 km upward continuation. The image employs vertical illumination. SBL, Southern Borrowdales Lineament.

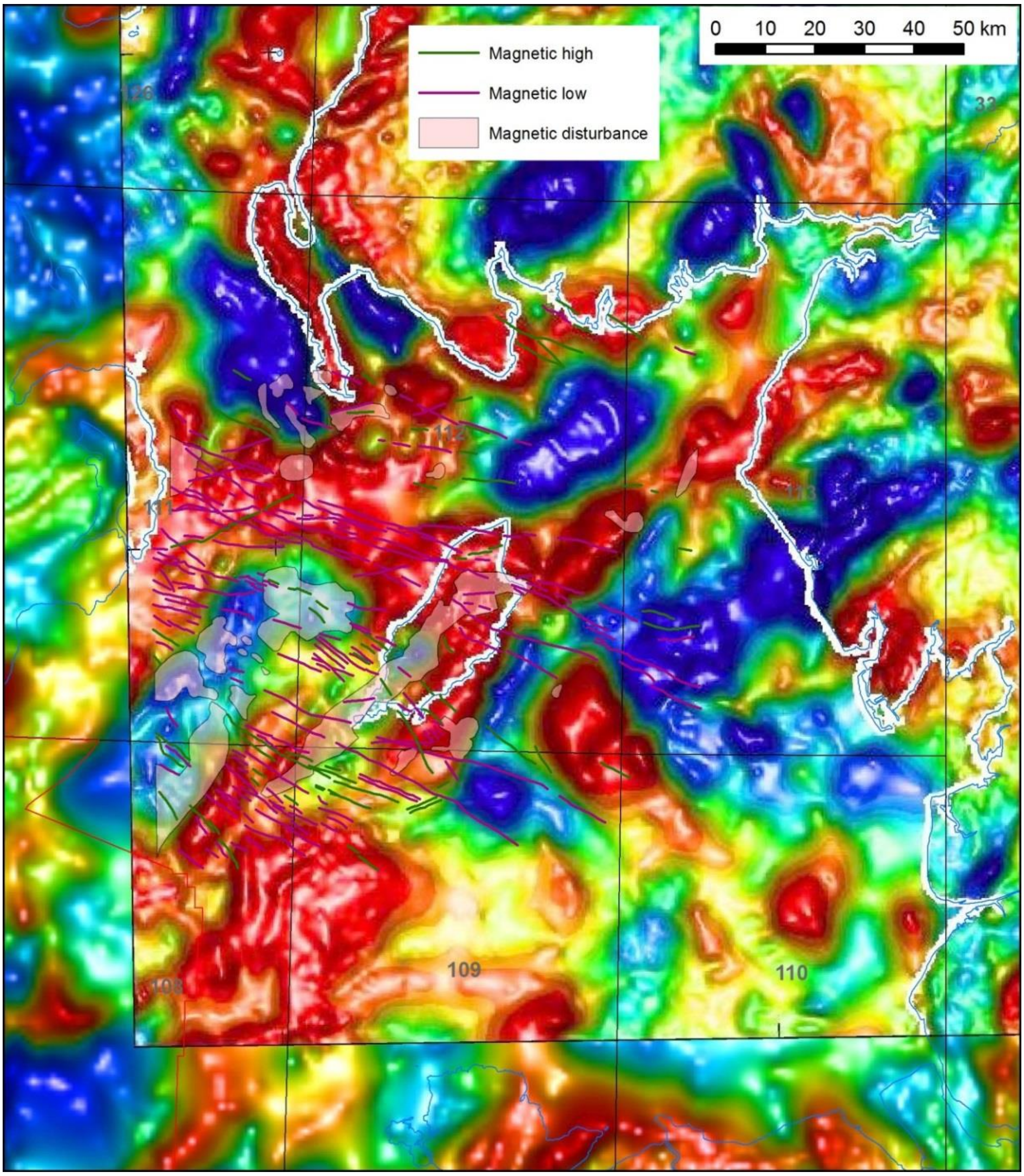


Figure 14 Magnetic features (see Figure 12) overlain on gravity field, as shown in Figure 13.

When the magnetic features identified in the Isle of Man area are overlain on the gravity image, the association between magnetic disturbances related to Palaeogene sills and the Peel Basin becomes clear (Figure 14; area around the south-east corner of Quadrant 111). Data from the northern extremity of the detailed magnetic coverage indicate that a similar association applies in the North Channel Basin (Chadwick et al., 2001).

4 Structural history

This section provides a summary of existing work to give a regional structural history and incorporates reference to new work described in section 5, as well as any previously documented implications for petroleum systems.

4.1 PRECAMBRIAN

The crust of the southern part of the area of investigation (North Wales, Anglesey and adjacent offshore areas) was generated as volcanic and sedimentary complexes in magmatic arc-trench systems during late Proterozoic time. Many early tectonic lineaments (Menai Straits Fault Zone, Gibbons and Woodcock, 1987) are associated with the accretion and dispersal of various terranes along the margins of Gondwana in Neoproterozoic to Cambrian time. Many of the lineaments (Dinorwic, Berw) have a SW-NE trend, are relatively straight (implying steep upper crustal geometry) and have been serially reactivated (Acadian sinistral transpression, Devono-Carboniferous extension etc).

The crust of the northern part of the area (Midland Valley, Scottish Highlands) was generated throughout Proterozoic time. A Neoproterozoic supracrustal metasedimentary sequence, the Dalradian Supergroup, was strongly deformed during the Grampian phase of the Caledonian Orogeny. Its southern limit is marked by the Highland Boundary Fault, which forms the northern boundary of the area of investigation.

4.2 EARLY PALAEOZOIC

The crust in the central part of the study area comprises early Palaeozoic sedimentary complexes belonging to several different terranes forming part of the Avalonian (Monian, Lakesman) and Laurentian (Southern Uplands, Midland Valley) margins of the Iapetus Ocean, and accreted during the Caledonian Orogeny. Numerous major tectonic lineaments have a typical SW-NE 'Caledonide' trend. These include the Carmel Head Thrust of northern Anglesey, and reactivations of the earlier Monian lineaments; the Causey Pike Thrust and Southern Borrowdale Lineament of the Lake District (Section 3); the numerous accretionary tracts of the Southern Uplands massif; and numerous faults with this trend within the Southern Highlands terrane. In the offshore region, inferred Caledonide basement structures include the Barrule Thrust north-west of the Isle of Man (Chadwick et al., 2001).

4.3 DEVONIAN

During the Acadian phase of the Caledonian Orogeny, all of the lineaments identified above were reactivated within a sinistrally transpressive regime, associated with the late orogenic collapse of the Caledonian mountains chain, stretching from the Appalachians through Ireland and Scotland to Greenland and Norway. The most obvious element of this regime is the Great Glen-Walls Boundary Fault system. Devonian strata are thickest in the north of the study area, forming the molasse to the Caledonian Orogen, locally filling intramontane basins. In the south, Devonian strata are more limited in development (Anglesey). In such a tectonic regime, W-E extension is anticipated. Basins related to such an orientation are tentatively identified within the Orcadian Basin (Leslie et al., 2015) but are less clearly identified in the study area, except perhaps, in the orientation of some rift basins (North Channel, Strangford Lough) within the Southern Uplands massif and the Peel Graben of the Isle of Man.

4.4 CARBONIFEROUS

An extensional- transtensional tectonic regime persisted into Carboniferous time. Although a general north-south extensional regime has been invoked in Tournaisian to Visean time (Leeder, 1982), extension occurred on faults with a diversity of orientations, but with reactivation of earlier basement structures (of various trends) being a common feature, e.g. in the Northumberland Basin (De Paolo et al., 2009). Such a situation reflects partitioning of the tectonic regime (Leslie et al., 2015). East of the study area, in Lancashire, the Bowland Basin reflects deeper water deposition in a basin bounded by SW-NE trending faults (Pendle Monocline etc) representing reactivations of earlier basement structures (Kirby et al., 2000). The Solway Basin is the offshore continuation of the Northumberland Basin (Chadwick et al., 2006), and is controlled by major bounding faults on a SW-NE trend. The Peel Basin along strike to SW, has a similar trend but opposite structural polarity and a very different basin setting in the Carboniferous (Figures 46, 54 below). However the evolution of both basins appears to have been strongly influenced by the extensional reactivation of underlying structures in the Caledonide basement. The Midland Valley (and Firth of Clyde basins) also exhibit a SW-NE trend, which persists up to the Highland Boundary Fault.

Carboniferous extension

Up to 5 km of Visean to late Westphalian (and possibly Stephanian) strata accumulated in the Quadrant 109 Basin (Jackson and Mulholland, 1993; Jackson and Johnson, 1996). The presence of a major half-graben (tilt-block) in Quadrant 109 is interpreted here, controlled by a major syndepositional bounding fault in the NW, the Eubonia-Lagman Fault System. This fault is also on a SW-NE trend. The eastern part of this major Carboniferous extensional basin was subsequently almost obliterated by Permian to Mesozoic extensional rifting and Cenozoic inversion. On the margins of the Carboniferous basin, in North Wales, the Isle of Man and Lake District (Ramsey-Whitehaven Ridge), an extensive shallow carbonate platform developed. In later Carboniferous (Namurian and Westphalian) times, post-extensional thermal subsidence was more regional in nature.

Early phase of Variscan inversion

Through Westphalian time, the impact of the Variscan Orogeny resulting from the collision of numerous Gondwana-derived terranes (Armorica, Central Massif, Bohemian Massif etc) with the southern margin of Laurussia (Ziegler, 1990; Pharaoh et al., 2006), became increasingly evident in Britain. Large-scale thrust and nappe emplacement occurred in southern Britain, south Wales and southern Ireland, but the region lay north of the Variscan Foldbelt, in its foreland. In late Westphalian C time, an early phase of inversion was followed by deposition of strata of the Warwickshire Group (Whitehaven Sandstone Formation in west Cumbria), above a regional unconformity (Eastwood et al., 1937; Akhurst et al., 1997; Waters et al., 2011).

In the East Irish Sea Basin, this study has identified SSW-ENE trending inversion structures both parallel to the Eubonia-Lagman Fault System in the north, and in a belt crossing the Godred Croven Platform farther south (Figure 15). The latter structures comprise a southward-vergent fold-thrust belt and are here correlated with the Ribblesdale Fold Belt onshore in Lancashire. Such structures are here interpreted as compressional reactivations of early Carboniferous extensional structures, which were themselves reactivations of structures in the Caledonide basement (see Section 5 below). This study has shown that the early inversion structures are cut by the north-south trending faults of the Permian-Mesozoic Main Graben, such as the Godred Croven Fault and the western boundary fault of the East

Deemster Basin. North of the Ramsey-Whitehaven Ridge, both the Solway and Peel basins suffered strong inversion on SSW-NNE ‘Caledonoid’ trends, with uplift and erosion of most of the post-rift (Namurian to Westphalian) successions (Jackson et al., 1995; Newman, 1999). Variscan reversal of the Maryport Fault is demonstrated by the preservation of a much more complete post-rift sequence on its footwall block (Ramsey-Whitehaven Ridge) than in the Solway Basin, its hangingwall block (Chadwick et al., 1993).

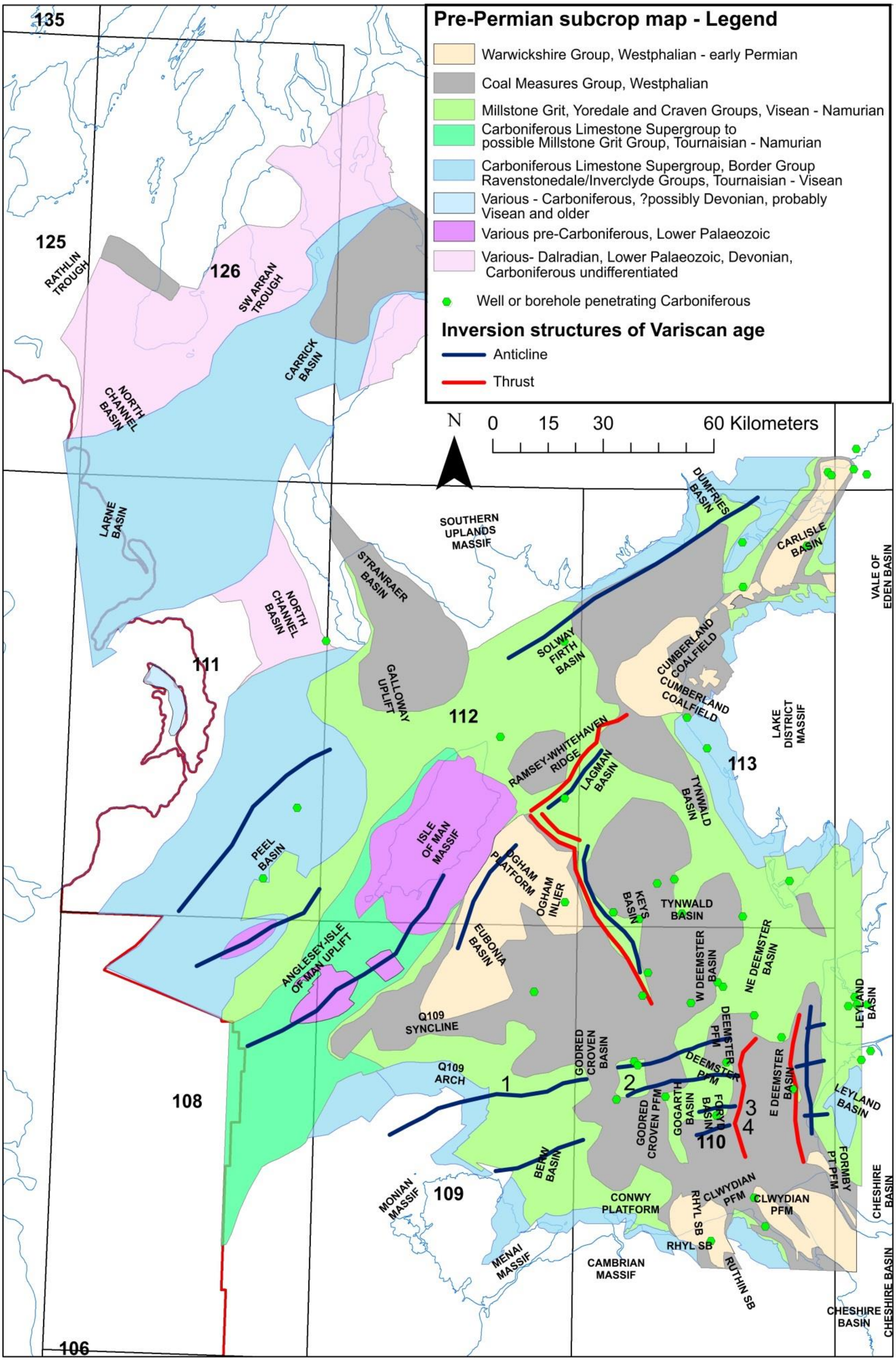


Figure 15 Pre-Permian subcrop map showing key Variscan inversion structures. Numbered fold axes are referred to in the text.

Later Variscan phase of inversion

In latest Carboniferous (Stephanian) time, the final phase of the Variscan Orogeny is associated with collisional orogeny in the Urals, resulting in W-E oriented compressional stress (Coward, 1995). In the study area, inversion occurred along NNW-SSE to N-S trending faults such as the Keys Fault, the western marginal fault of the East Deemster Basin and the Formby Point Fault System (sections 5 below). It is conceivable that inversion on faults with this trend could have occurred in a distributed deformation system in one Variscan phase of inversion. However, as described above, this study has shown that the N-S trending faults bounding the incipient main graben in late Permian to Triassic time cut the earlier inversion structures; and evidence will be presented (section 5) for the development of interference structures (e.g. the so-called Ribble Estuary Inlier) between these and a second phase of Variscan inversion.

4.5 PERMIAN

In early Permian time, volcanism is associated with incipient rift zones in central Europe (Rotliegendes in Germany and Central North Sea, Exeter Traps in southern Britain) (Southern Permian Basin Atlas, 2010), together reflecting lithospheric extension of the supercontinent of Pangaea (Ziegler, 1990; Coward, 1995). Following the basin inversion and regional uplift described above, erosion of Coal Measures strata from the crests of inversion anticlines adjacent to the Keys, Lagman, Lake District Boundary and Formby Point faults has been observed in the current study. In the Exeter area, Worcester Basin (reactivating Malvernoid, late Precambrian structural trends), Knowle, Stafford and Cheshire basins, north-south trending rifts began to develop in response to west-east extension (Whittaker, 1985; Chadwick and Evans, 1995). These rifts propagated with stepwise, *en-echelon* offsets through the region, from the East Irish Sea Basin with localised thickening of the Appleby Group, through the North Channel and marginal Larne Basin, into the western Scottish offshore basins (this study). The Solway and Peel basins subsided less, and are elongated SW-NE, reflecting the dominating constraint of the reactivated basement structure within the Iapetus Convergence Zone. Nevertheless, it is notable that the majority of small to medium-sized intrabasinal normal faults (Chadwick et al., 2001) take up the new N-S trend, as in the Cheshire Basin (Chadwick, 1997).

4.6 TRIASSIC

In the Triassic, continuing west-east extensional stress perpetuated the pattern established by late Permian time. In northern Germany and Denmark, very rapid subsidence is associated with north-south trending graben (Glückstadt Graben etc) with significant halokinesis already evident by late Triassic time (Southern Permian Basin Atlas, 2010). The East Irish Sea Basin was a major graben within this system, receiving up to 5km fill of Sherwood Sandstone Group clastic sedimentary rocks and Mercia Mudstone Group mudstones and evaporites (Jackson and Mulholland, 1993). The Lagman and Keys faults are associated with large (>500 m, and up to 2200 m, respectively) throws of the base of the Mercia Mudstone Group (Chadwick et al., 2001), with a likely significant post-Triassic component.

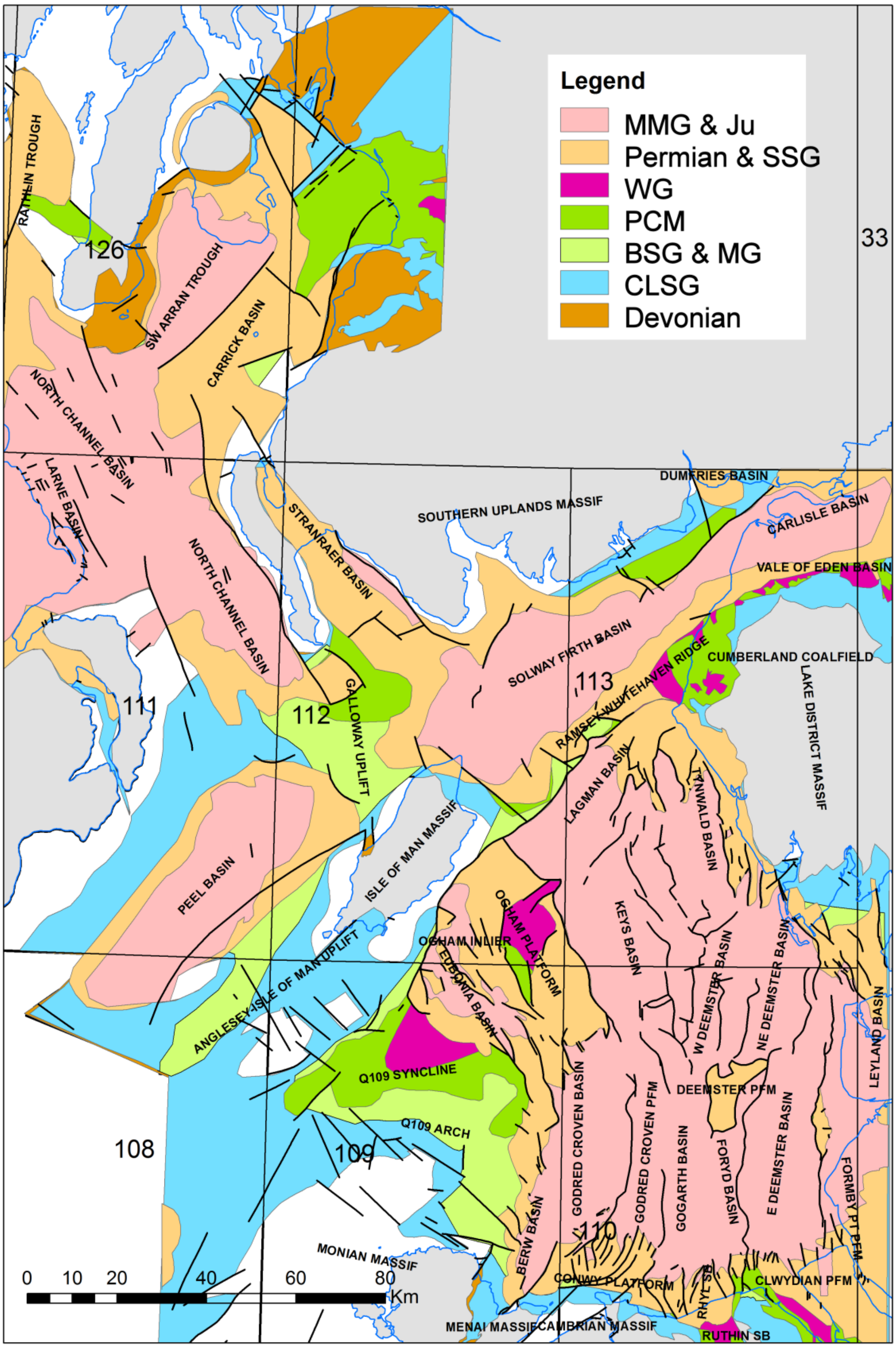


Figure 16 Pre-Quaternary subcrop map with named tectonic elements. Key to geology: Ju, Jurassic; MMG, Mercia Mudstone Group; SSG, Sherwood Sandstone Group; WG, Warwickshire Group; PCM, Pennine Coal Measures; MG, Millstone Grit; BSG, Bowland Shale Formation; CLSG, Carboniferous Limestone Supergroup. Partly based on BGS 1:250,000 offshore DigMap BGS©NERC.

4.7 JURASSIC

Small relict outliers of Lias (early Jurassic) strata in the Solway (Warrington et al. 1997), Peel Basin (Chadwick et al., 2001) and East Irish Sea Basin (Jackson and Mulholland, 1993) indicate that subsidence in the Triassic rift system continued into Jurassic time. Evidence for middle and late Jurassic subsidence has been removed subsequent to Cenozoic inversion, uplift and erosion. The magnitude of post-Triassic displacement is difficult to estimate due to this erosion, but it is likely that the Lagman and Keys faults, together with the Maryport, Portpatrick, Loch Ryan and St Patrick faults, suffered significant normal movement (Jackson and Mulholland, 1993). In the Keys Basin, West Deemster Basin and elsewhere, low-angle detachment style faulting and associated halokinetic activity occurred at this time (Jackson and Mulholland, 1993) The development of the so-called platy-illite layer, interpreted as a palaeo-hydrocarbon-water contact (Bushell, 1986; Woodward and Curtis, 1987), is a distinctive feature of the Morecambe fields (Colter and Barr, 1975; Cowan, 1991; Stuart, 1993). The illite has been dated at 180 Ma by the K-Ar method (Bushell, 1986), reflecting accumulation of an early hydrocarbon charge in early Jurassic time. Detailed study of the surface in wells, reported by Knipe et al. (1993), shows that the layer tilts to west in the Keys Basin, and to east in the West Deemster Basin as a result of later extension on the bounding (Keys, Crosh Vusta) faults of the system and uplift of the field area during Cenozoic inversion (Stuart and Cowan, 1991).

4.8 CRETACEOUS

Up to 2 km of sedimentary rocks were deposited in the Wealden Basin of southern Britain in early Cretaceous time, but evidence for the Cretaceous subsidence history in the Irish Sea Basin has been completely removed. Chalk is preserved beneath Palaeogene lavas in Northern Ireland. Apatite fission-track analysis indicates that for parts of the Ramsey-Whitehaven Ridge, maximum post-Variscan burial was achieved in early Cretaceous time (Green et al., 1997). This was associated with peak generation of hydrocarbons from Carboniferous source rocks throughout the region. Soon after this, a fall in relative sea level and erosion resulted in the Late Cimmerian Unconformity, found throughout the British Isles (Whittaker, 1985). The reduction in confining pressure may have been enough to allow early formed hydrocarbons, principally oil, to escape early reservoir structures in gentle roll-over anticlines associated with the shallow detachment tectonics in the centre of the Main Graben, towards roll-over traps at the marginal faults (this study).

4.9 CENOZOIC

Regional uplift

Opening of the Atlantic Ocean to the east of Greenland by Paleocene times associated with putative Icelandic Plume activity (e.g. Brodie and White, 1994; Nadin and Kuznir, 1995) resulted in the voluminous outpouring of lavas and the development of gabbroic-granitic intrusive complexes in the Inner Hebrides and in Northern Ireland just to west of the study area . Magmatic and thermal processes on a lithospheric scale resulted in regional thermal doming (epeirogenic uplift) of the crust (White, 1988) in Palaeogene or possibly, late Cretaceous, time (Cope, 1994; 1997). Apatite fission-track data from wells in the Solway and Peel basins indicate a phase of uplift at about 60 Ma (Newman, 1999).

Local thermal effects

A prominent set of olivine dolerite dykes, known as the Fleetwood Dyke Complex (Kirton and Donato, 1985), was intruded en echelon across the main graben of the East Irish Sea Basin, stretching from the southern edge of the Lagman Basin, crossing the Keys and Deemster basins towards the onshore at Fleetwood. The NW-SE trend exhibited by this dyke is also typical of basaltic dykes in the Isle of Man and the Peel Basin, clearly visible in aeromagnetic maps of the region (Chadwick et al., 2001, Figure 12), radiating from one of the intrusive complexes in Northern Ireland (Mourne, Slieve Gullion, Carlingford). Well 113/27-1 penetrated 365 m of dolerite in the inclined Fleetwood Dyke Complex in the vicinity of the Rhyl field. Disruption of evaporitic strata within the Mercia Mudstone Group seen on seismic from the Peel Basin may also be a manifestation of this igneous activity, and both wells 111/29-1 and 111/25-1A in this basin penetrated dolerites. Dykes and sills of similar composition are also common in the North Channel and South-West Arran basins, where there was a localised intrusive complex in Arran. Across the study area, the combination of enhanced regional and local heat flow to a further phase of hydrocarbon generation is considered below, see section 6.1.7.

Basin inversion

Superimposed on the regional, thermal uplift described above were the effects of crustal shortening, associated with the developing Alpine Orogeny in southern Europe. Inversion of the Solway Basin led to development of a major anticlinal structure in the hangingwall block of the Maryport Fault (Chadwick et al., 1993) on the northern side of the Ramsey-Whitehaven Ridge. On the the southern side of the Ramsey-Whitehaven Ridge, the reversal of the Lagman Fault led to the generation of small hangingwall anticlines (Chadwick et al., 2001). Flower structures and ‘pop-up’ structures are found along the Keys Fault and Formby Point Fault, reflecting the ‘buttressing’ effect of the margins of the Main Graben (this work). The Lennox Field (Haig et al., 1997) is trapped in such a structure. Throughout the East Irish Sea Basin, in Quadrant 109, the Eubonia Basin, the Godred Croven Platform fold and thrust belt and elsewhere, the seismic data interpreted here indicate the presence of gentle Cenozoic inversion anticlines superimposed on an earlier generation of Variscan inversion anticlines (see Figures 32, 33 below). Further tightening of the Variscan inversion anticlines during Cenozoic crustal compression resulted in the development of more open structures in the Permo-Triassic cover. In the Morecambe fields, lying at the heart of the Main Graben, further tightening of early (?Jurassic) roll-over anticlines increased the amplitude of the folds (this study). Iillite-rich diagenetic zones interpreted as palaeo-oil/water contacts (Bushell, 1986; Woodward and Curtis, 1987) were tilted few degrees during this deformation. The timing of these inversion events is imprecisely known. Outcrops on the Isle of Man show minor reverse faults which postdate the Palaeocene dykes (Quirk and Kimbell, 1997). Apatite fission-track data indicate a second phase of Cenozoic cooling at 25-20 Ma (Newman, 1999), compatible with the region being affected by the Oligo-Miocene phase of inversion found in southern Britain and the souther North Sea (Van Hoorn, 1987; Badley et al., 1989; Chadwick, 1993).

4.10 VARISCAN UNCONFORMITY SUBCROP AND SUPERCROP MAPS

For the Palaeozoic hydrocarbon systems in the Irish Sea, Variscan Unconformity pre-Permian subcrop and post-Carboniferous supercrop maps provide valuable information to aid assessment of the petroleum play. The subcrop map reveals potential source and reservoir rock distribution partially controlled by Variscan inversion, and laid bare by erosion in early Permian time (Figure 17). The supercrop map provides information on the distribution of potential reservoir and seals across the region (Fig. 18).

Subcrop map

Previous interpretations of the Variscan subcrop map illustrate additional Visean inliers (Smith, 1985) or Westphalian strata (inset to BGS, 1994) compared to the new version prepared for this study.

Visean and Tournaisian strata crop out in North Wales, Anglesey, and the Isle of Man and west Cumbria. Namurian strata are proven to form the subcrop onshore at Formby and in several offshore wells (Figure 17).

The Warwickshire Group is not definitively proved in wells offshore and is mapped only on seismic data, present within the Eubonia Basin, northern Quadrant 109, west of Whitehaven-Workington in the Solway Basin and north of the North Wales coast (Figure 40). The unit is missing from the main Carboniferous inversion in the centre of the basin (Figure 41).

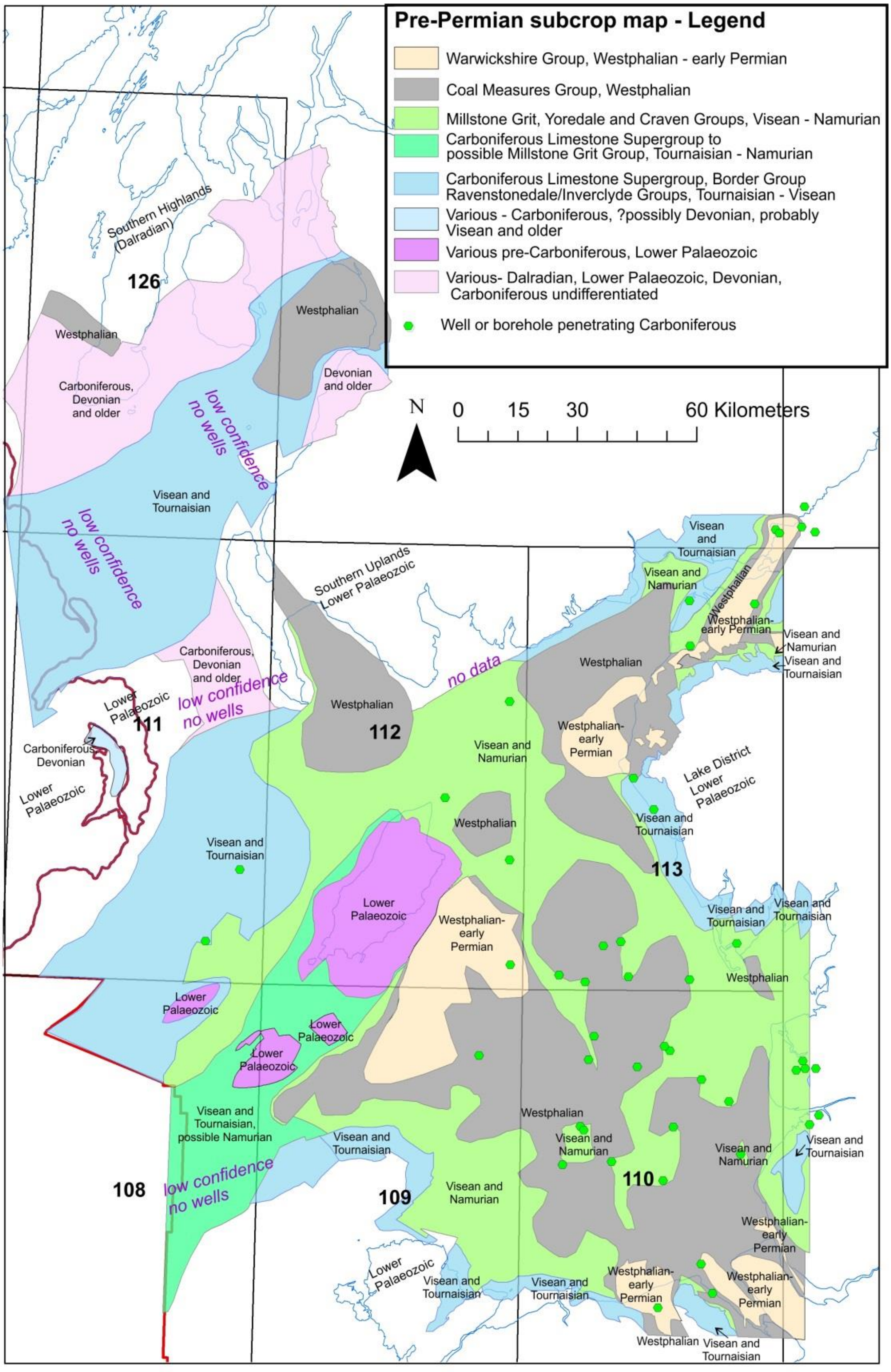


Figure 17 Variscan Unconformity (UVAR) or pre-Permian subcrop map for use at 1:1,500,000 to 1:250,000 scale.

Supercrop map

A hiatus exists between the Permian Appleby Group and underlying Carboniferous strata. Where the Appleby Group is absent, the Cumbrian Coast Group directly overlies the Variscan unconformity e.g. from offshore Lancashire to the Morecambe fields (Figure 18) and then via the Ogham Inlier towards the SW (based on sparker mapping at the seabed; BGS, 1994). The supercrop map shown is consistent with BGS (1994) where the Sherwood Sandstone Group is shown in some very small areas south-east of the Isle of Man. Sherwood Sandstone also forms the supercrop onshore in small areas of Lancashire near Preston.

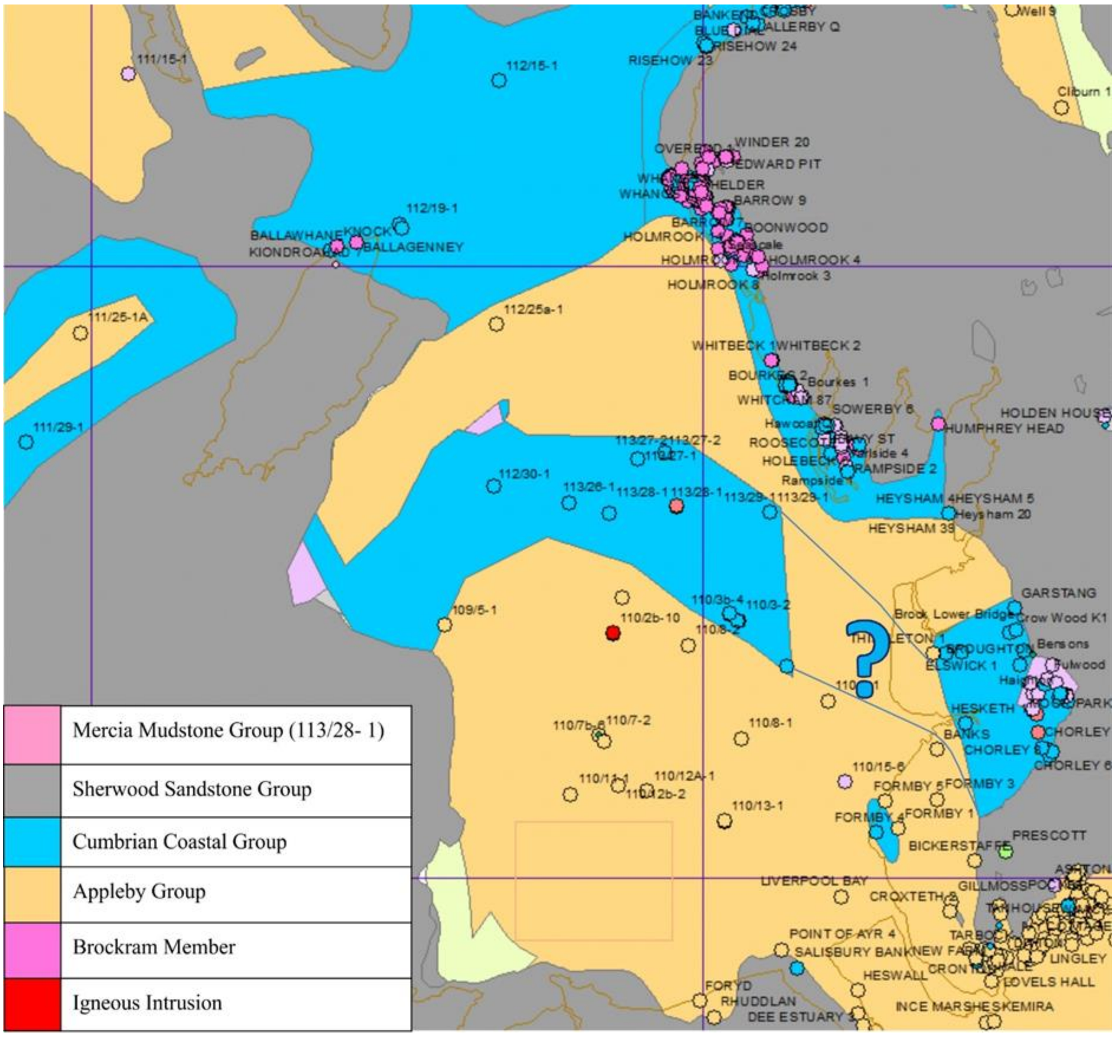


Figure 18 Variscan Unconformity Supercrop map for use at 1:1,500,000 to 1:250,000 scale.

5 Basin evolution

This section describes the principal characteristics of the Irish Sea basins based on the new seismic interpretation (Pharaoh et al., 2016a) and representative seismic sections. Note that the basin and fault terminology followed (shown in Figure 5) is that pertaining to the well-known Permo-Trias basin systems (e.g. Jackson & Mullholland, 1993; BGS, 1994) and not that of the underlying Carboniferous basins. The East Irish Sea Basin is structurally complex, as a consequence of the structural history described in section 4, and one of the deepest post-Variscan basins in the British sector. For convenience in this account, the East Irish Sea Basin is divided into 'Main Graben' and 'Marginal' graben/areas (Figure 5). The former refers to the depocentre of the basin, in which over 3 km (and locally e.g. in the Keys Basin, more than 5 km) of Permian, Triassic and Jurassic strata have been preserved. The late Palaeozoic strata beneath these areas remain deeply buried. By contrast, late Palaeozoic rocks were not as deeply buried beneath the shallow Marginal graben and platforms, and come to outcrop at seabed across a significant part of the region (Figure 9).

The seismic interpretation was done on the best quality data where horizons could be clearly identified, and then propagated through onto lines with poor data resolution to give the fullest possible model for gridding. The variable seismic data quality at Carboniferous levels and sparsity of deep well control have led to challenges in interpretation, particularly of the deeper picks. The interpretation of the surfaces contains a strong model-driven element, evidenced by the onshore relationships and areas where seismic picks can be made with the greatest confidence.

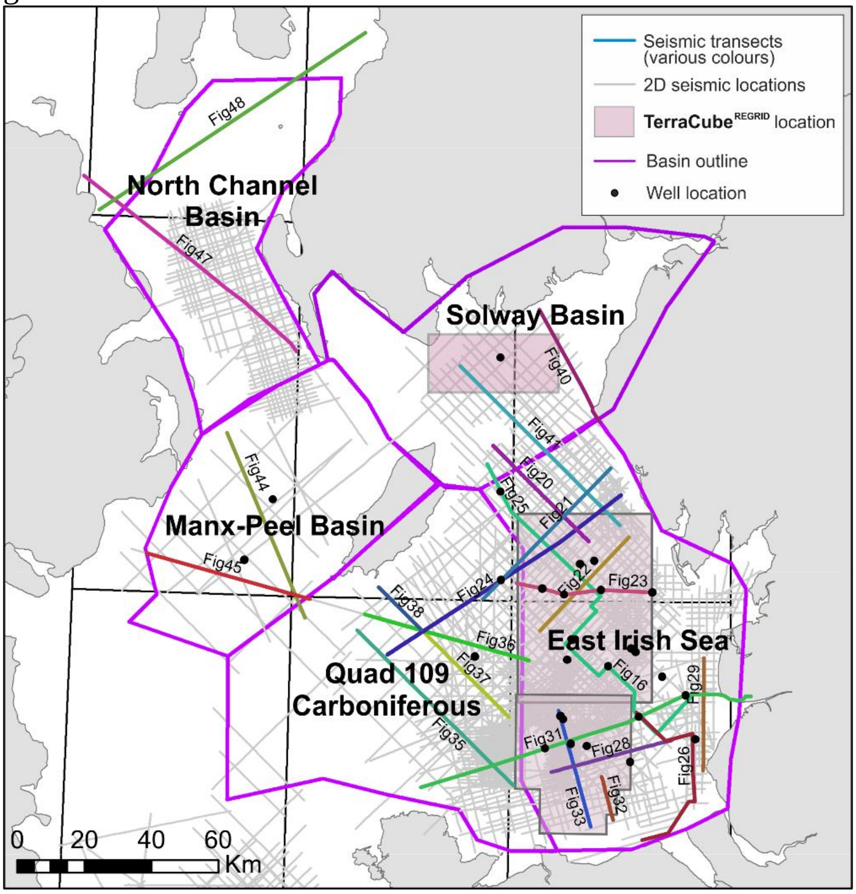


Figure 19 Location of seismic images in next section.

5.1 MAIN GRABEN OF THE EAST IRISH SEA BASIN

Lagman Basin

The Lagman Basin is the northernmost component of the East Irish Sea Basin (Jackson et al., 1987), bounded in the west by the Keys Fault; to north by the Lagman Fault, with the Ramsey-Whitehaven Ridge in its footwall; and in the south by the SW-NE trending Sigurd fault system. The displacements on the latter fault systems decrease eastwards and die out into the Cumbrian Massif. The Lagman Fault is sub-planar and dips to SE at about 50°. The base Permian level is downthrown by up to 3000 m (1.3 s TWTT in Figure 21), a significant part of which occurred in late or post Triassic time (Chadwick et al., 2001). The Sherwood Sandstone Group shows significant syndepositional thickening towards the fault (Figure 20). The Sigurd Fault is a complex structure, variable in geometry and throw, offset by a number of minor, near vertical faults with E and ENE trend, interpreted by Chadwick et al., (2001) as transfer faults. Although considered a 'new' fault of Permo-Triassic age by Chadwick et al., (2001), the interpretation presented in Figure 20 suggests significant pre-Permian displacement, e.g. of the Acadian (Caledonian) Unconformity (UCAL). Only one well (112/25a-1) penetrated the Carboniferous here, proving 378 m of Yoredale Group overlying 90 m of Carbonifereous Limestone Supergroup to TD. The present investigation suggests that Coal Measures have been completely removed following Variscan inversion (contrary to BGS, 1994).

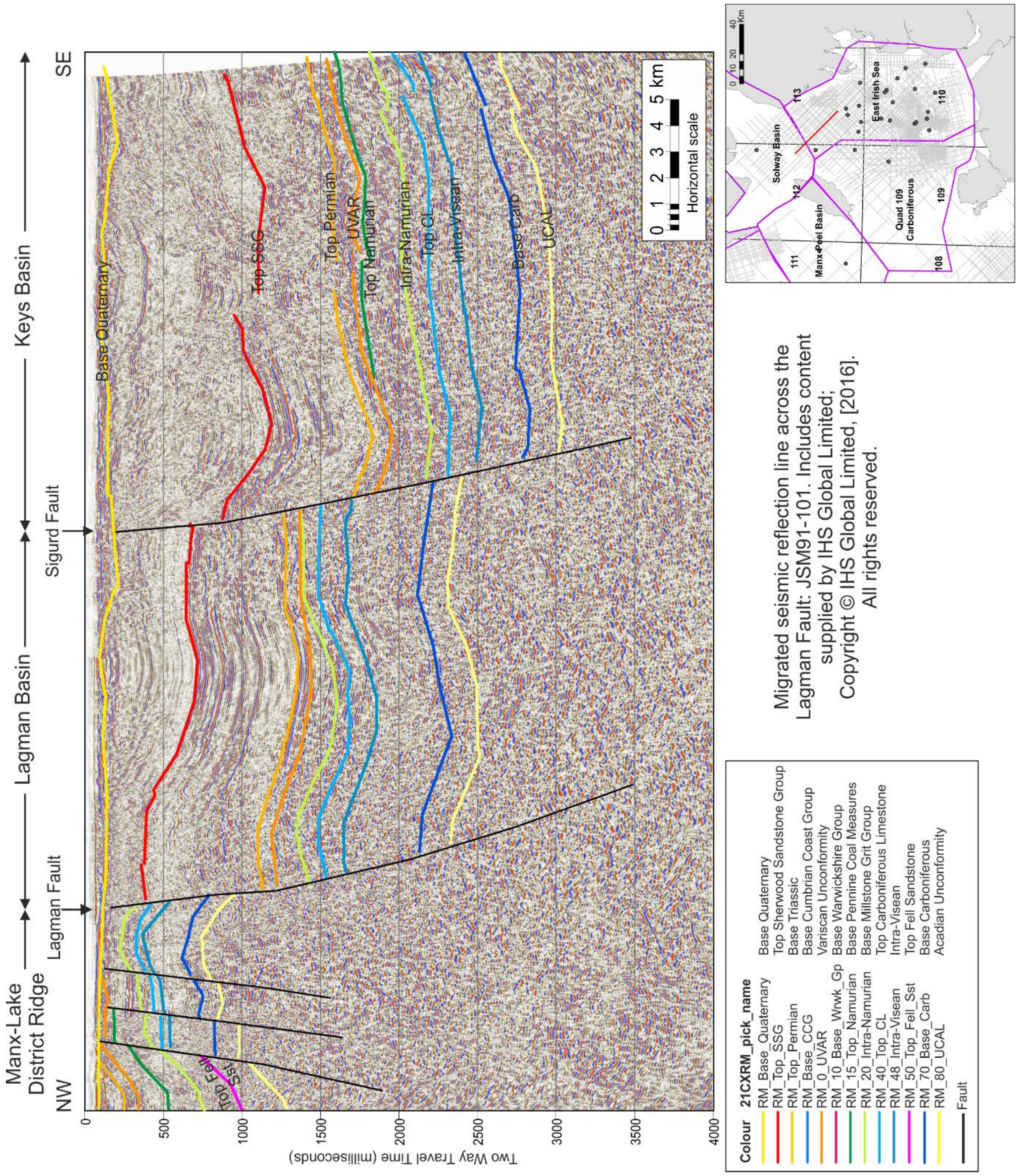


Figure 20 Migrated seismic reflection line across the Lagman Fault: JSM91-101. Includes content supplied by IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

Keys Basin

Separated from the Ogham Platform in the west by the NW-SE trending Keys Fault (Figure 21), and from the Lagman Basin by the Sigurd Fault, this is one of the deepest Permo-

Triassic rifts in the UK sector, containing in excess of 5000 m of strata (2 s TWTT in Figure 20, 2.35 s TWTT in Figure 21). The Keys Fault is a major sub-planar normal fault which dips ENE at between 50° and 65° (Chadwick et al., 2001). The throw at base Permian level is locally 4000 m, although towards the Lagman Fault this decreases to 1500 m due to the development of a number of more northerly trending splays. The Mercia Mudstone Group sequence is particularly thick at up to 3000 m (Jackson and Johnson, 1996), and contains thick units of salt. Subsequent halokinesis has resulted in spectacular salt diapir structures and detachment tectonics with low-angle listric faults and 'raft tectonics' (Jackson et al., 1987; Arter and Fagin, 1993; Akhurst et al., 1997). The seismic line depicted Figure 21 crosses from the Ogham Platform towards the deepest part of the Keys Basin. Figure 22 is located farther south, where the platform has a thicker Permo-Triassic cover, and running across the Millom and Rhyl fields. Well 113/27- 3 (Millom field) encountered 156 m of Millstone Grit, while well 113/27- 1 (Rhyl field) farther east, proved more than 140 m of Coal Measures. Figure 23 is a W-E line across the same structure, well 113/26- 1 proving some 590 m of Coal Measures on the northern flank of the Variscan inversion structure. These interpretations suggest that the Millom field overlies a significant Variscan faulted inversion anticline, buttressed against the Ogham Platform. The Millom Field Sherwood Sandstone Group reservoir structure was formed by the further growth of this Variscan structure during Cenozoic inversion (Figure 23). Further evidence for Variscan inversion on the Keys Fault comes from the evidence for excision of the Coal Measures, caused by erosion following uplift, in the sub-surface mapping (BGS, 1994). Note also that base Permian is significantly deeper in 113/27-1 (2918 m) than in 113/27-2 (1778 m). The seismic image in Figure 22 reflects severe velocity pull-up as a consequence of the overhanging Fleetwood Dyke Complex. Well 113/27-1 drilled 365 m of olivine dolerite. A small outlier of Lias Group in the centre of the basin (BGS, 1994), was proved by shallow borehole 89/11A (Warrington, 1997). The Jurassic strata, which may be up to 700 m thick (Chadwick et al., 2001), occupy a small graben bounded by listric normal faults within the Mercia Mudstone Group. This indicates that salt tectonics within the Mercia Mudstone Group were active well into Jurassic time, if not later (Chadwick et al., 2001).

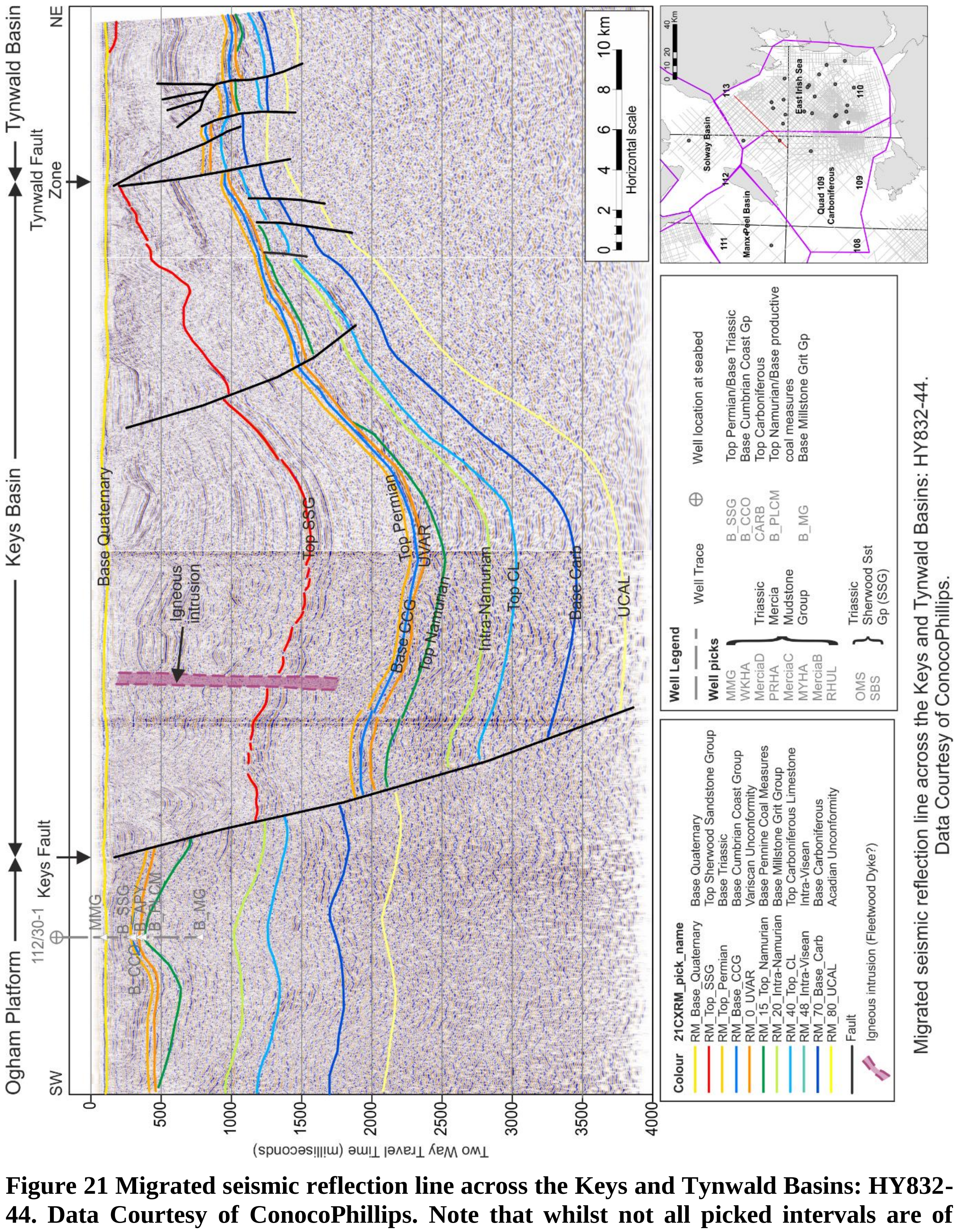


Figure 21 Migrated seismic reflection line across the Keys and Tynwald Basins: HY832-44. Data Courtesy of ConocoPhillips. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

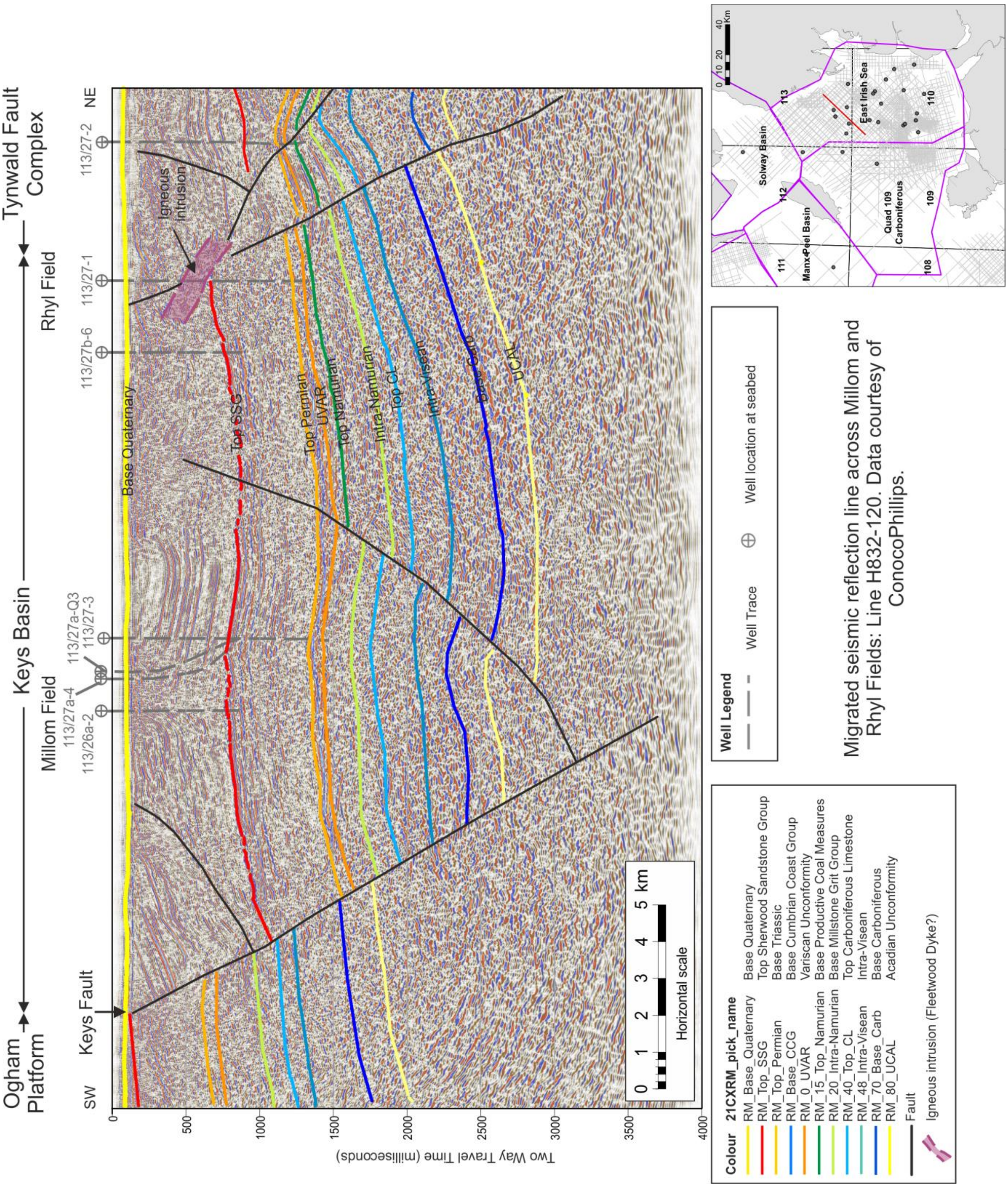


Figure 22 Migrated seismic reflection line across Millom and Rhyl Fields: Line H832-120. Data courtesy of ConocoPhillips. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

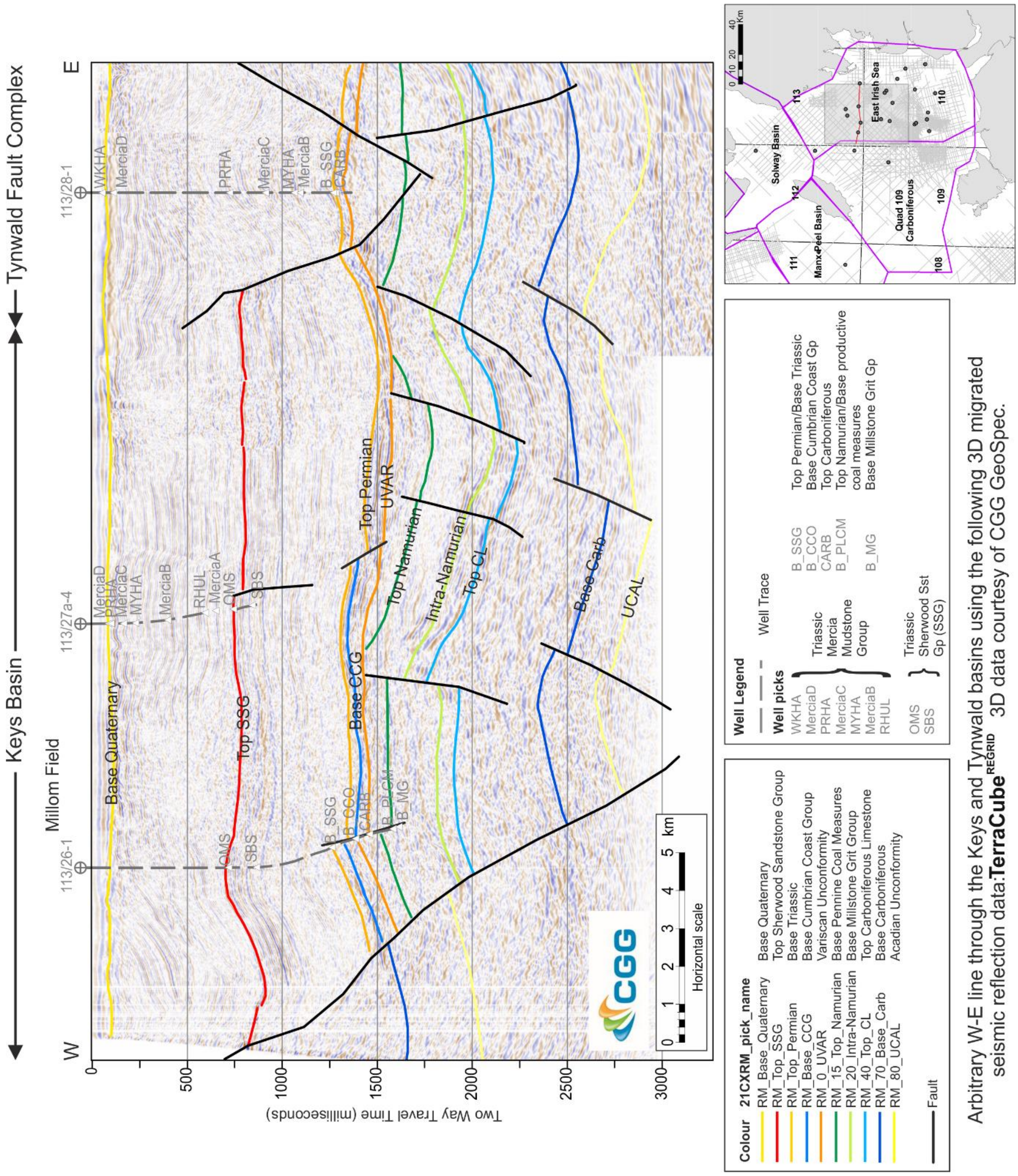


Figure 23 Arbitrary W-E line through the Keys and Tynwald basins using the following 3D migrated seismic reflection data: TerraCube[REGRID] 3D data courtesy of CGG GeoSpec. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

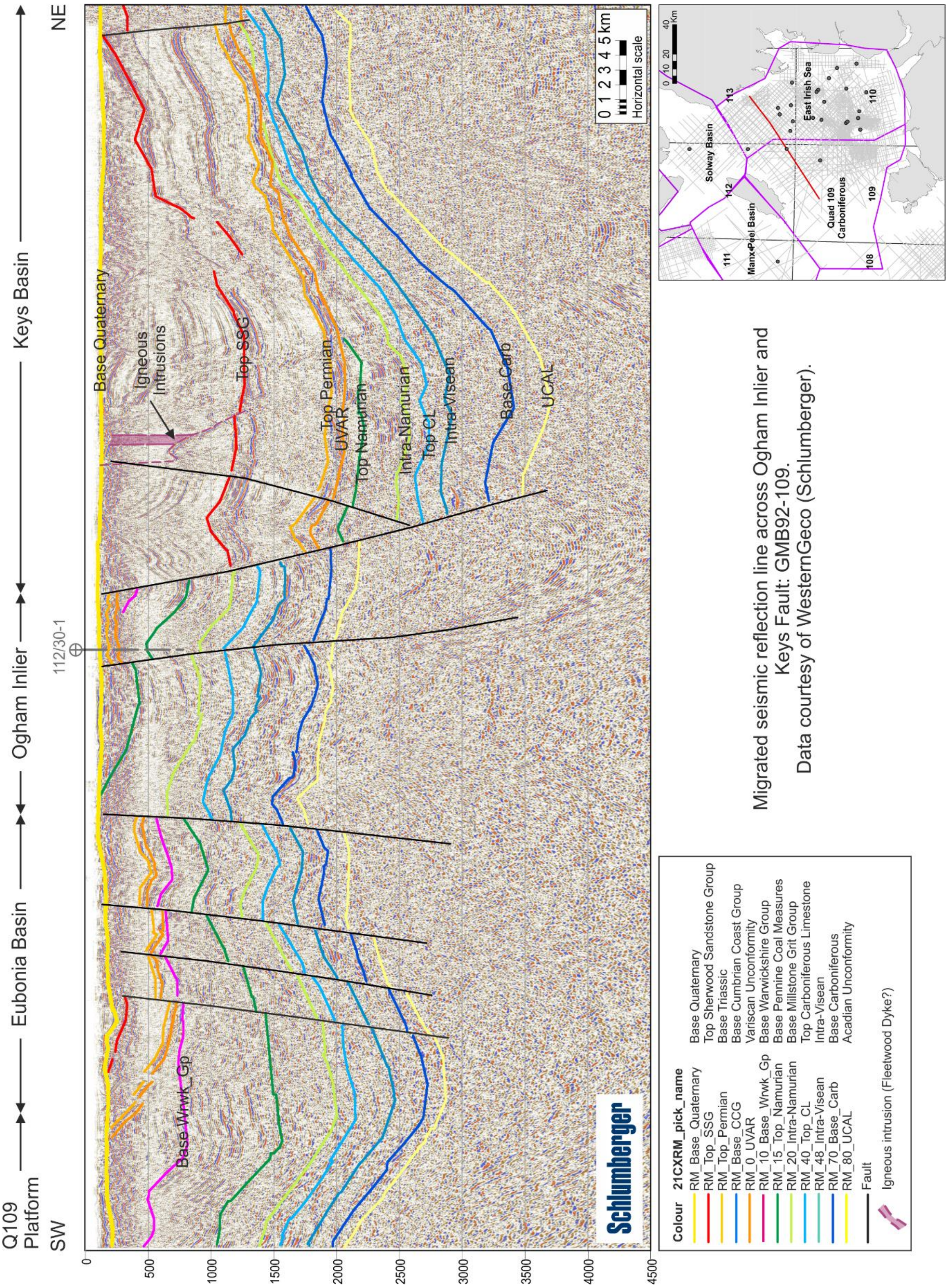


Figure 24 Migrated seismic reflection line across Ogham Inlier and Keys Fault: GMB92-109. Data courtesy of WesternGeco (Schlumberger). Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

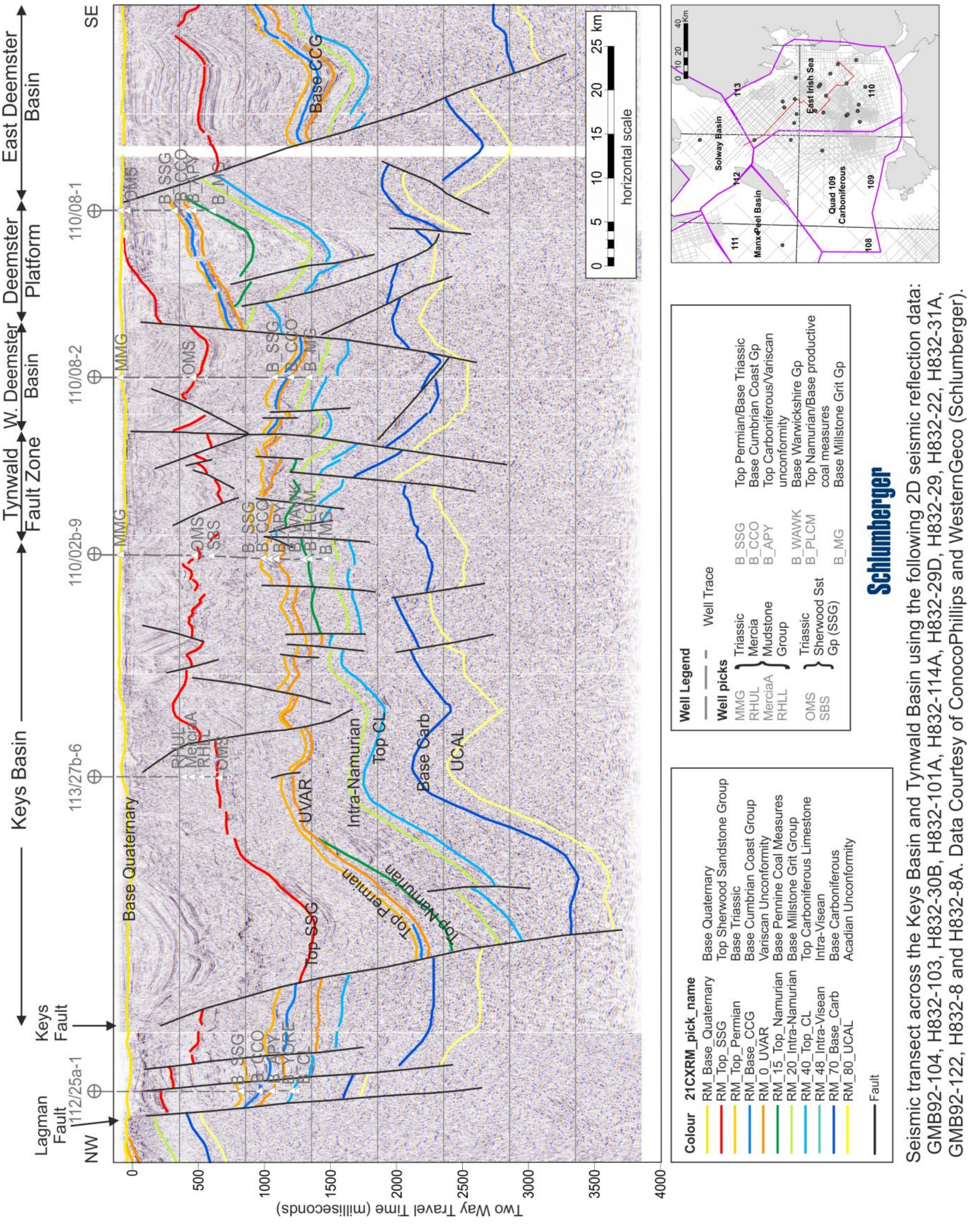


Figure 25 Seismic transect across the Keys Basin and Tynwald Basin using the following 2D seismic reflection data: GMB92-104, H832-103, H832-30B, H832-101A, H832-114A, H832-29D, H832-29, H832-22, H832-31A, GMB92-122, H832-8 and H832-8A. Data Courtesy of ConocoPhillips and WesternGeco (Schlumberger). Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

Tynwald Basin

The Tynwald Basin, lying offshore to the west of the Cumbrian Massif, is separated from the Keys Basin by the Tynwald Fault Complex (Figure 5). The sole well penetration of Carboniferous in this basin is 113/27-2, lying within the fault complex to east of the Rhyl Field, which proved Pennine Lower Coal Measures, Millstone Grit Group, Bowland Shale Formation and Carboniferous Limestone Supergroup (Figure 22). BGS (1994) indicate a broad swathe of Namurian subcrop at the eastern edge of the basin, suggesting widespread excision of the Coal Measures following inversion along the line of the Lake District Boundary Fault System.

West Deemster Basin

The Morecambe fields straddle the southern end of the Tynwald Fault Complex, where it separates the southern part of the Keys Basin (containing the Morecambe North Field and part of the south field) from the West Deemster Basin (SE part of the South Morecambe Field, and Bains Field). Figure 25 demonstrates the complexity of the structure in this area, not only in the Triassic cover, which is partially detached from its Carboniferous substrate; but also in the Carboniferous, where complex folding beneath the southern end of the Deemster Platform is comparable to that seen farther to the SSW, on the Godred Croven Platform (see below). The well 110/08-2 in the South Morecambe Field encountered Millstone Grit, Coal Measures having been removed beneath the centre of the southern part of the Keys Basin. Figure 25 clearly shows a syncline of Coal Measures beneath the southern part of the Deemster Platform, narrowly missed by well 110/08-1. The western margin of the East Deemster Basin is another zone of excision associated with Variscan inversion (Figure 16).

NE Deemster Basin

This basin is separated from the West Deemster Basin by the Crosh Vusta Fault Complex. The zone of Coal Measures excision noted above at the eastern margin of the West Deemster Basin, continues part of the way southward into this basin. The only well penetrating the base Permian is 113/29-2, which is believed to have entered Namurian strata, although this is poorly documented.

East Deemster Basin

Figure 26 is the continuation to south-east of Figure 25, along the axis of the East Deemster Basin. The early Carboniferous sequence appears to be of relatively uniform thickness, though the interpretation is low confidence due to seismic resolution at depth. The most notable feature is the rapid thinning of the Namurian sequence southwards towards the coast of North Wales, and thickening of the Coal Measures in the same direction. Thus, in the Liverpool Bay well (110/20-1), 510 m of Namurian (base not penetrated) and 540 m of Coal Measures (no Warwickshire Group) are interpreted; Point of Ayr 4 (SJ18NW/20) proved 312 m of Warwickshire Group, 9 m of Upper Coal Measures, 333 m of Middle Coal Measures, 101 m of Lower Coal Measures (to TD). The other significant Carboniferous well penetration is 110/15- 6 in the Lennox Field (Figure 30). As this entered Namurian strata in the footwall of the Formby Point Fault, it is described as part of the Basin Margin (see below). Figure 26 is a W-E seismic line showing excision of the Coal Measures on both margins of the East Deemster Basin. Farther west, beneath the Hamilton fields in the Foryd-Gogarth Basin, the folds affecting the Carboniferous sequence are the same as those to be described below, in the section 4.3 North Wales margin.

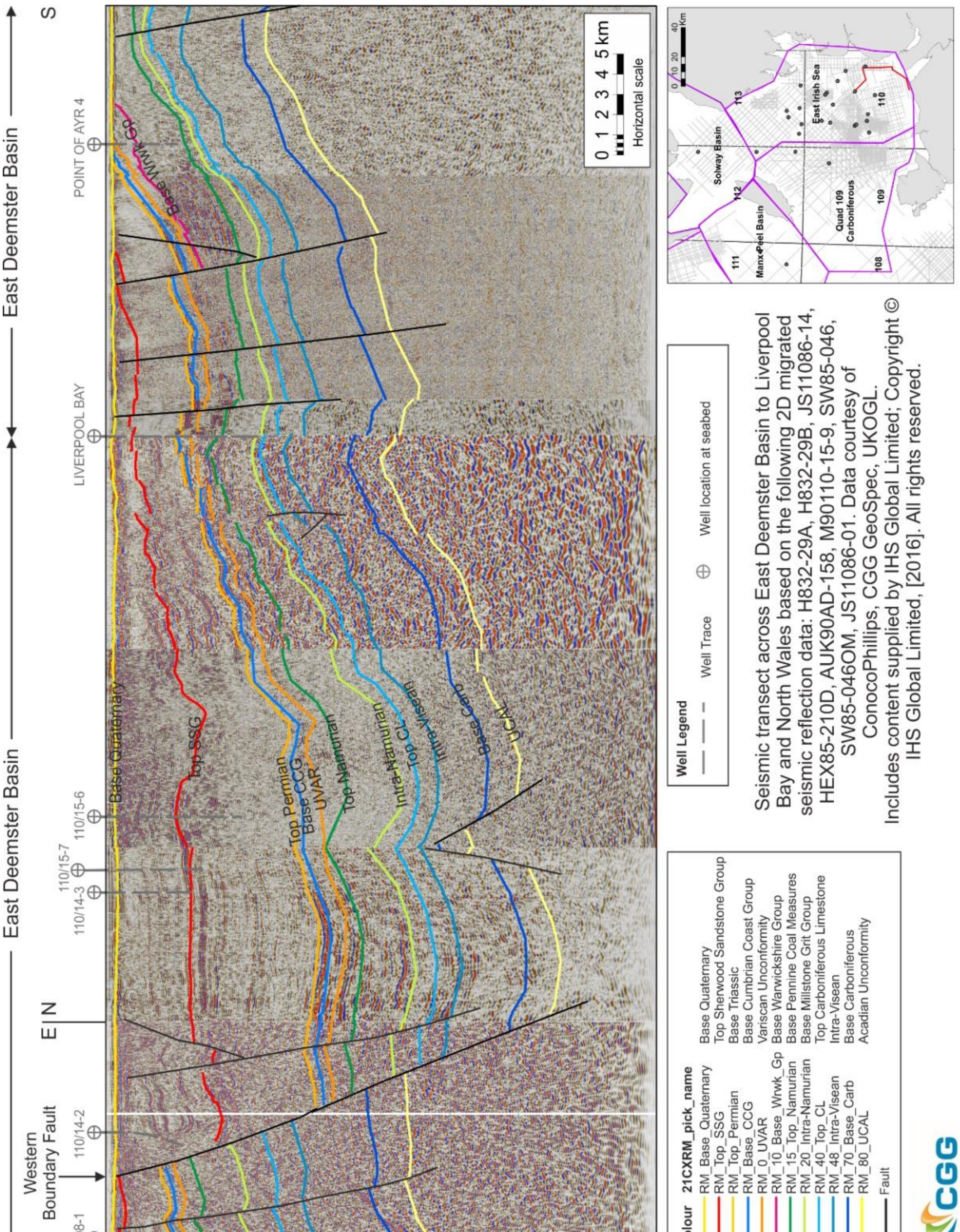


Figure 26 Seismic transect across East Deemster Basin to Liverpool Bay and North Wales based on the following 2D migrated seismic reflection data: H832-29A, H832-29B, JS11086-14, HEX85-210D, AUK90AD-158, M90110-15-9, SW85-046, SW85-046OM, JS11086-01. Data courtesy of ConocoPhillips, CGG GeoSpec, UKOGL. Includes content supplied by IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

Petroleum system

Figure 27 illustrates key aspects of the hydrocarbon system within the northern part of the Main Graben. Note the deep burial (> 6km) of putative Namurian source rocks (unproven) beneath the deep Permian-Mesozoic graben system in the Keys and Tynwald basins, and erosion of Westphalian Coal Measures in Variscan inversion structures at the margins. Reservoir qualities of the late Carboniferous sandstones are likely to be poor, except perhaps on the Ogham Platform. A good regional seal and caprock (Mercia Mudstone Group) is present across the central and eastern part of the section.

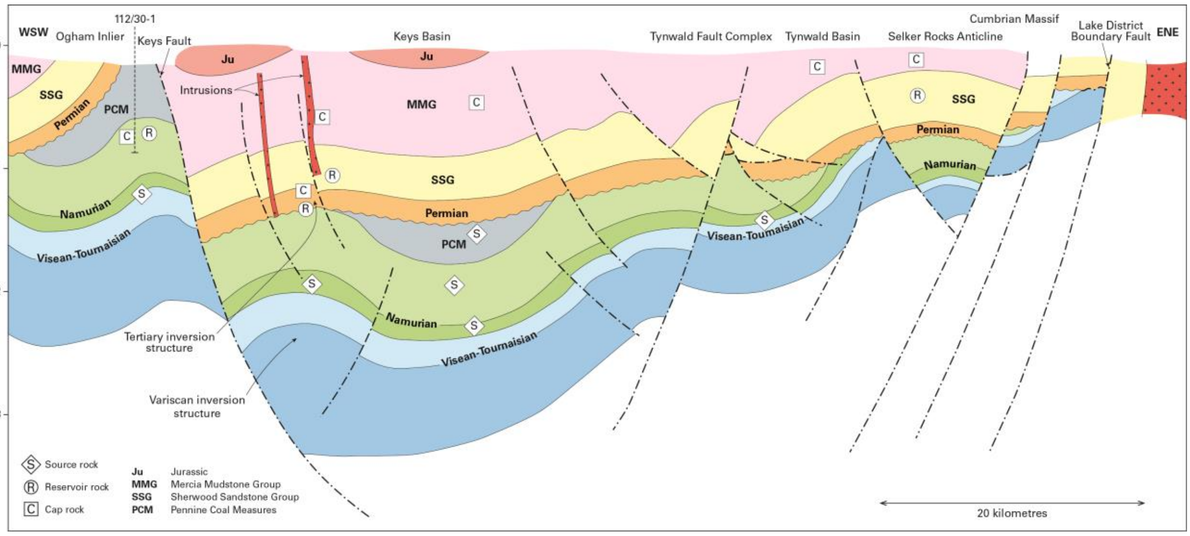


Figure 27 Synoptic cartoon to illustrate principal elements of the hydrocarbon system in the northern part of the Main Graben

5.2 MARGINS OF THE EAST IRISH SEA MAIN GRABEN

Cumbria-Lancashire Margin

Extending southwards from the eastern end of the Ramsey-Whitehaven Ridge (Jackson et al., 1993), the Lake District Boundary Fault System links en echelon into the Formby Point Fault System and its continuation into the onshore, the western boundary fault of the Lancashire Coalfield (Figure 5). Further details of the Cumbrian part of the system are presented in publications (e.g. Akhurst et al., 1997) stemming from the NIREX investigations offshore Sellafield. A thick Carboniferous succession, including the late Westphalian age Whitehaven Sandstone is cut out rapidly southwards as a result of Variscan inversion.

On the Formby Platform, east of the Formby Point Fault, an inlier of Namurian (Ribble Estuary Inlier) occurs within the Coal Measures. The present study has recognised that this is a Variscan fold/fault interference structure, further enhanced by superimposed Cenozoic inversion and likely results from the superimposition of structures from both the early (W-E) and late (N-S) phases of Variscan inversion described in section 4. It remains to be tested if this complicated history would have resulted in reservoir breaching of Carboniferous sandstones, or whether it is possible for further fields in the vicinity of, but underlying, Lennox (which is at the Triassic Ormskirk Sandstone level) can be identified (Figures 28, 30).

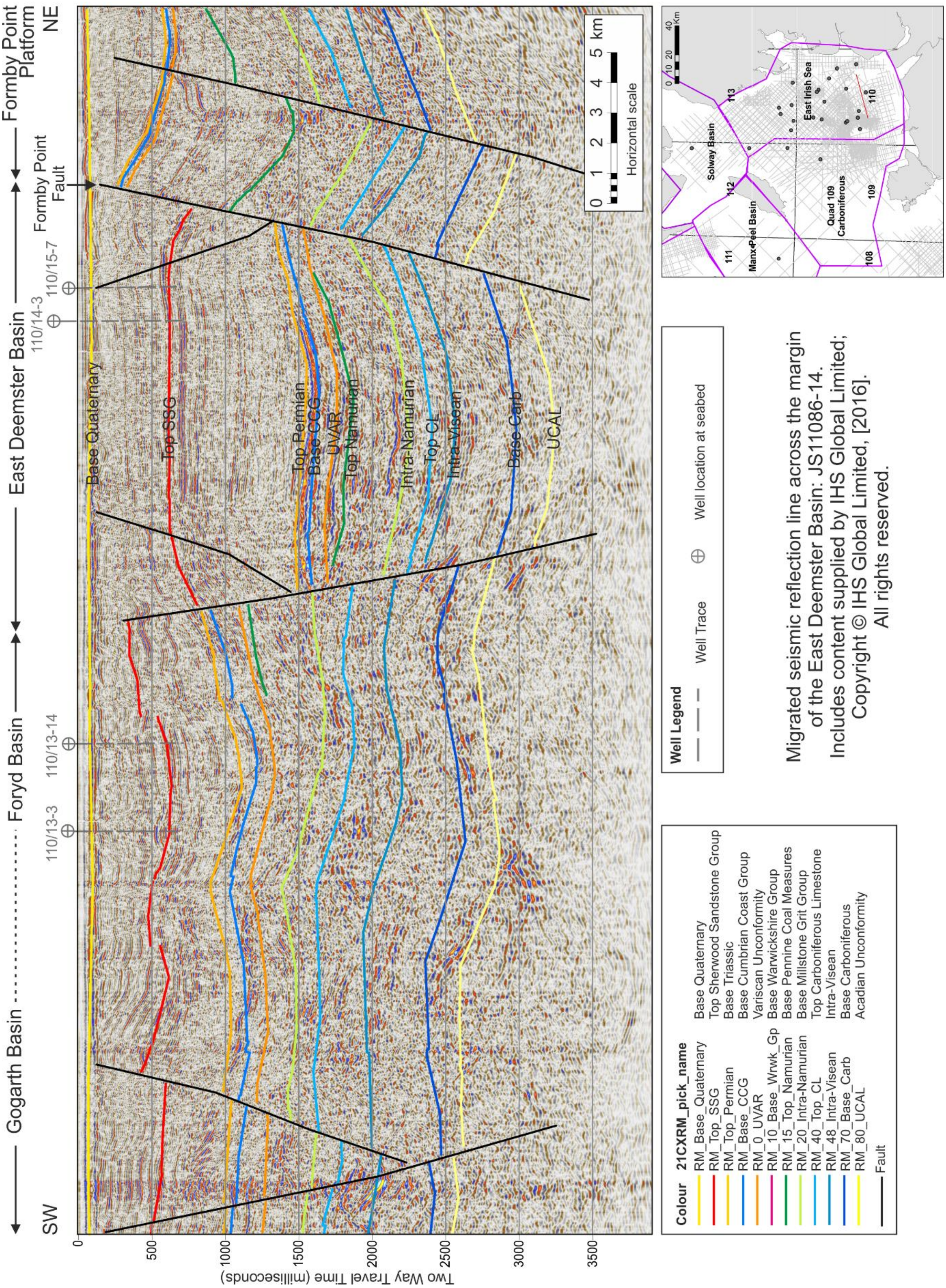


Figure 28 Migrated seismic reflection line across the margin of the East Deemster Basin: JS11086-14. Includes content supplied by IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

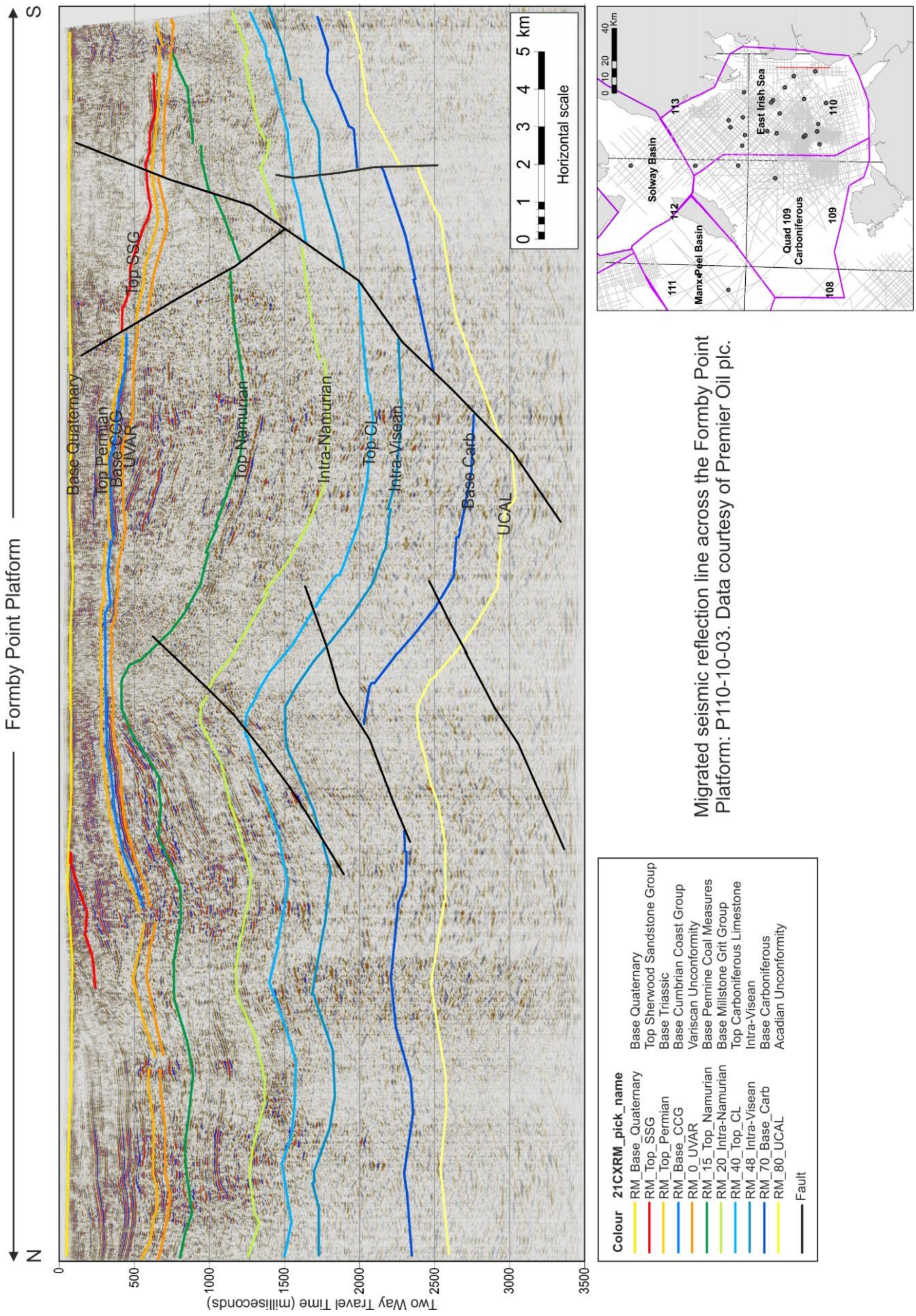


Figure 29 Migrated seismic reflection line across the Formby Point Platform: P110-10-03. Data courtesy of Premier Oil. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

Figure 30 illustrates key aspects of the hydrocarbon system within the southern part of the Main Graben. Note the shallower burial (c. 4 km) of Namurian source rocks, except beneath the deeper East Deemster Basin. Reservoir qualities of the late Carboniferous sandstones are uncertain. A good regional seal and caprock (Mercia Mudstone Group) is present across the region.

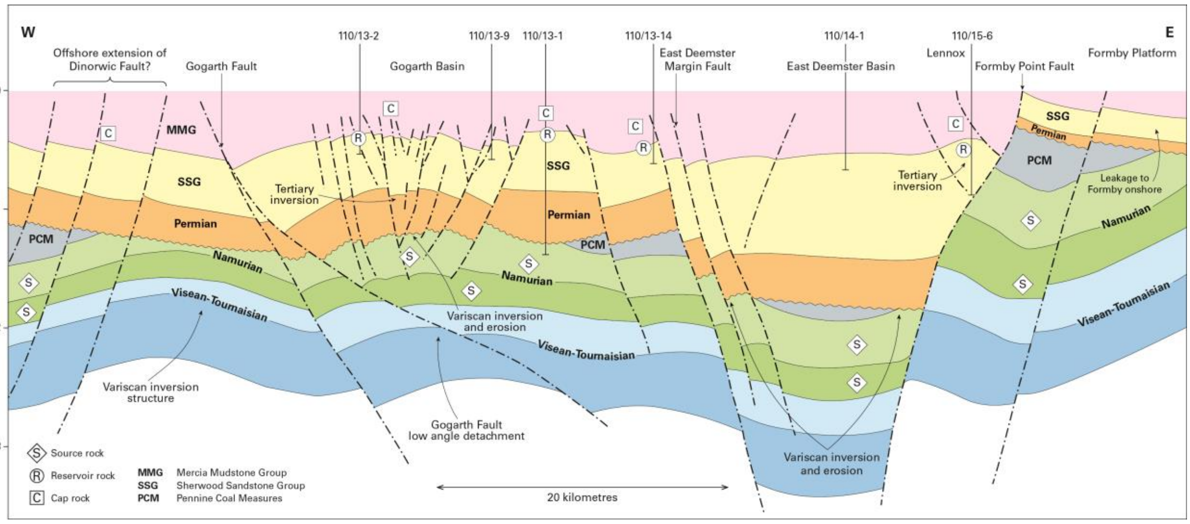


Figure 30 Synoptic cartoon to illustrate principal elements of the hydrocarbon system in the southern part of the Main Graben

5.3 NORTH WALES MARGIN

Figure 31 is a W-E seismic line parallel to the southern margin of the East Irish Sea Basin, located about 25 km offshore. It shows a series of Permo-Triassic half-graben structures, to west of the East Deemster Basin, predominantly controlled by westward-dipping faults, interspersed with platforms. From east to west these are the Deemster Platform, Foryd Basin, Gogarth Basin, Godred Croven Platform and Godred Croven Basin. The thickness of the Permo-Triassic sequence, which is predominantly eastward-dipping, varies between 1.3 s TWTT in the basins to 0.8 ms TWTT or less on the platforms. The graben-bounding faults have a dominantly N-S orientation, although some deflection into the Caledonide SW-NE trend is observed closer to the north Wales coast. Here, a number of even shallower platforms (Clwydian, Conwy, Rhyl Sub-basin) were identified by BGS (1994). Figure 31 shows that the predominant dip of the Carboniferous sequence is towards the west, so that Coal Measures are preserved beneath the Godred Croven Basin and Platform but largely eroded beneath the Gogarth Basin, Deemster Platform and East Deemster Basin. Further clarification is provided by NNW-SSE trending arbitrary lines through 3D coverage of the Godred Croven Platform (Figures 32 and 33). These show a gently undulating base Permian surface, at about 1.3 s TWTT. The Douglas Field (Yaliz, 1997) is located within a faulted rollover anticline in the hangingwall of the Gogarth Fault, which is interpreted as a low-angle detachment here (Figure 30). The Carboniferous sequence is folded into a series of anticlines and synclines, while several oblique sets of reflections are interpreted as thrust faults underlying the anticlines and detaching below the Acadian (Caledonian) Unconformity level.

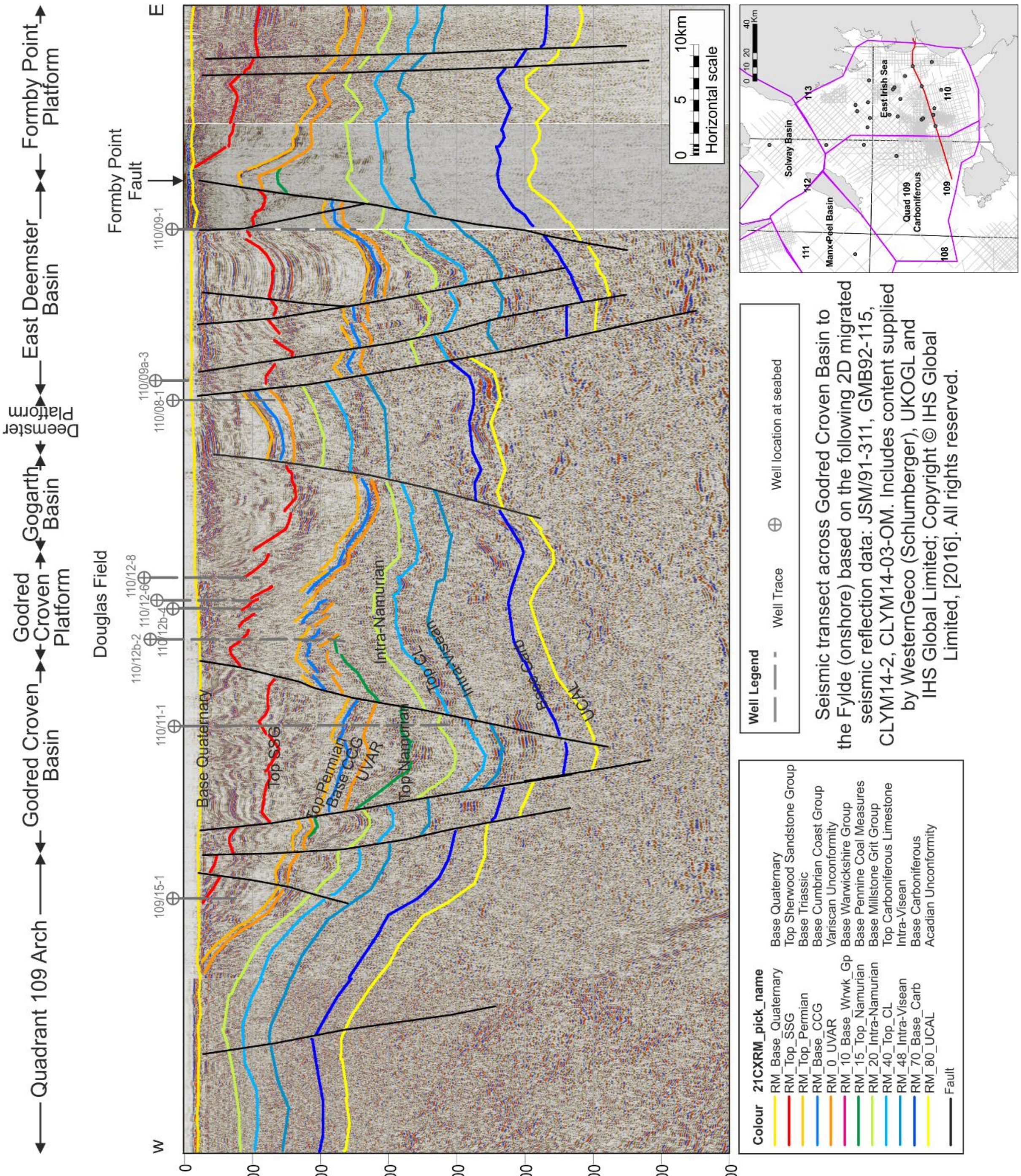


Figure 31 Seismic transect across Godred Croven Basin to the Fylde (onshore) based on the following 2D migrated seismic reflection data: JSM/91-311, GMB92-115, CLYM14-2, CLYM14-03-OM. Includes content supplied by WesternGeco (Schlumberger), UKOGL and IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

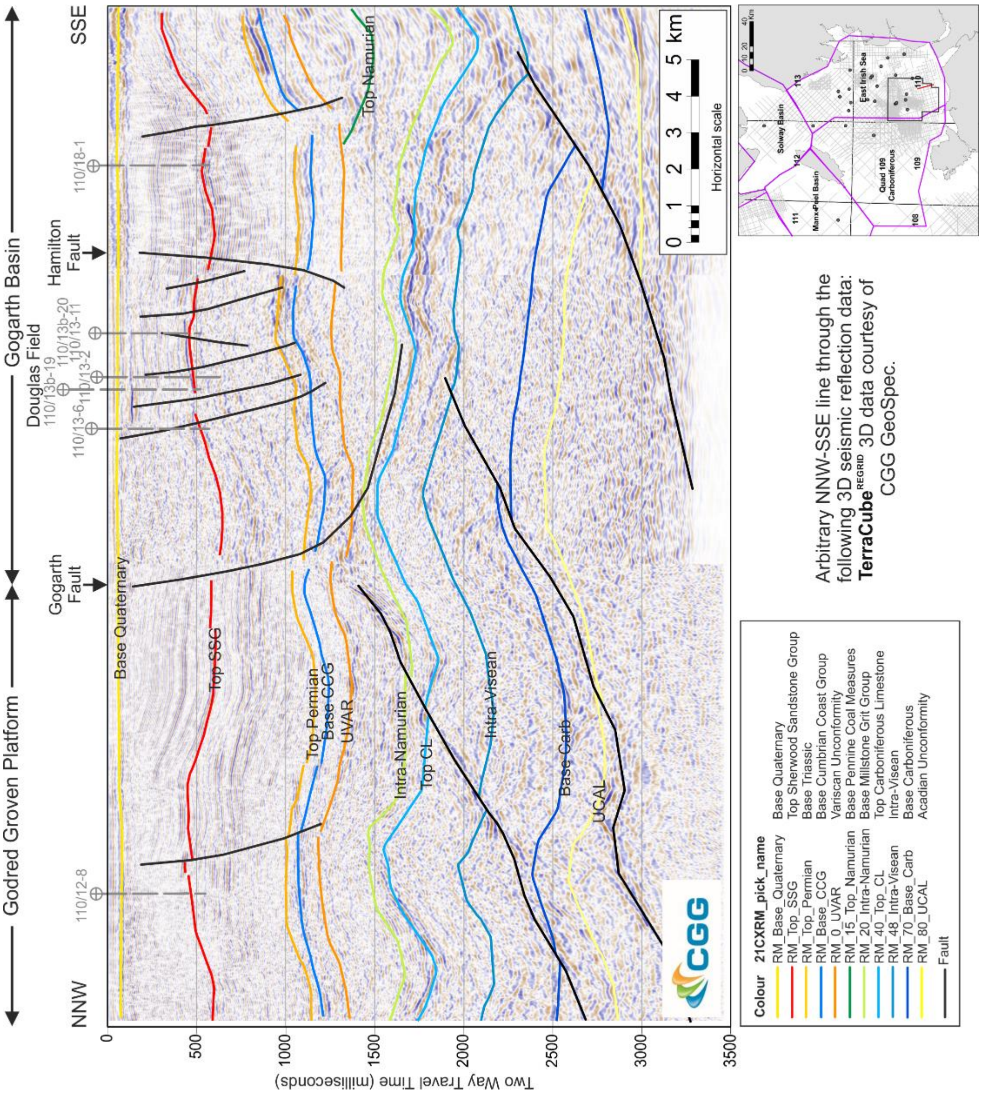


Figure 32 Arbitrary NNW-SSE line through the following 3D seismic reflection data: TerraCube[REGRID] **3D data courtesy of CGG GeoSpec. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.**

Four sub-parallel WSW-ENE trending anticlinal axes have been mapped in the pre-Permian succession across the Godred Croven Platform, numbered consecutively 1 to 4 from north to south (Figure 15). The Conwy Field and Hamilton North overlie fold axis 2; the Douglas Field straddles fold axes 2 and 3; Hamilton East, Hamilton and Douglas straddle fold axes 3 and 4. At least some of these gentle Cenozoic inversion anticlines result from further growth of the original Variscan fold/thrust stack. Well 110/13- 1 in the Hamilton Field reached TD in Bowland Shale Formation beneath Millstone Grit Group.The similarity of these structures to those in the Ribblesdale Fold Belt onshore (Kirby et al., 2000) is striking, and a correlation via the fold structures identified beneath the Deemster Platform, described above, is proposed. Figure 33 is an arbitrary line through 3D data, parallel to and about 7 km west of Figure 32. Very similar structures, ramp anticlines, are observed. Well 110/12b- 2, 4 km along strike to west of the Conwy Field, proved Coal Measures above Millstone Grit Group. 110/07b- 6 (deviated) proved over 500 m of Bowland Shale Formation beneath the Millstone Grit Group. The interpretation of the seismic data presented in Figure 33 suggest this well reached TD just short of the Visean. The Berw Basin off Anglesey, like the adjacent Godred

Croven Basin, is controlled by a westward dipping major syn-depositional fault. Local inversion near the Berw Fault reflects Cenozoic uplift (Jackson et al., 1995).

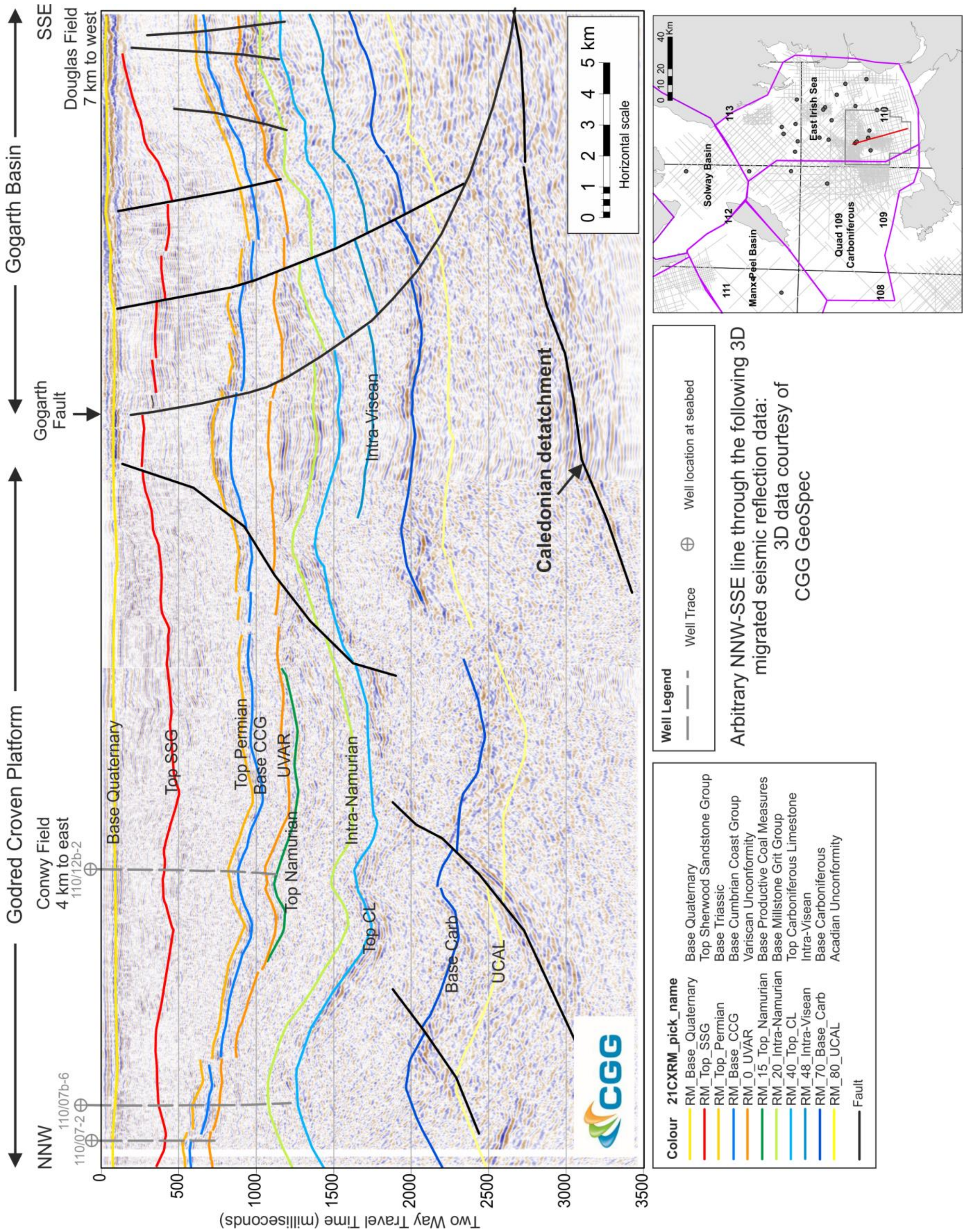


Figure 33 Arbitrary NNW-SSE line through the following 3D migrated seismic reflection data: TerraCube**REGRID** **3D data courtesy of CGG GeoSpec. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.**

Figure 34 illustrates key aspects of the hydrocarbon system along a north-south transect across the Main Graben. The Namurian Bowland Shale is thicker adjacent to the Deemster Platform, a position analogous to the Bowland Trough. Note the development of a fold/thrust belt in response to Variscan compression, and further growth of these folds during Cenozoic inversion. Reservoir qualities of the late Carboniferous sandstones are uncertain. A good regional seal and caprock (Mercia Mudstone Group) is present across the region.

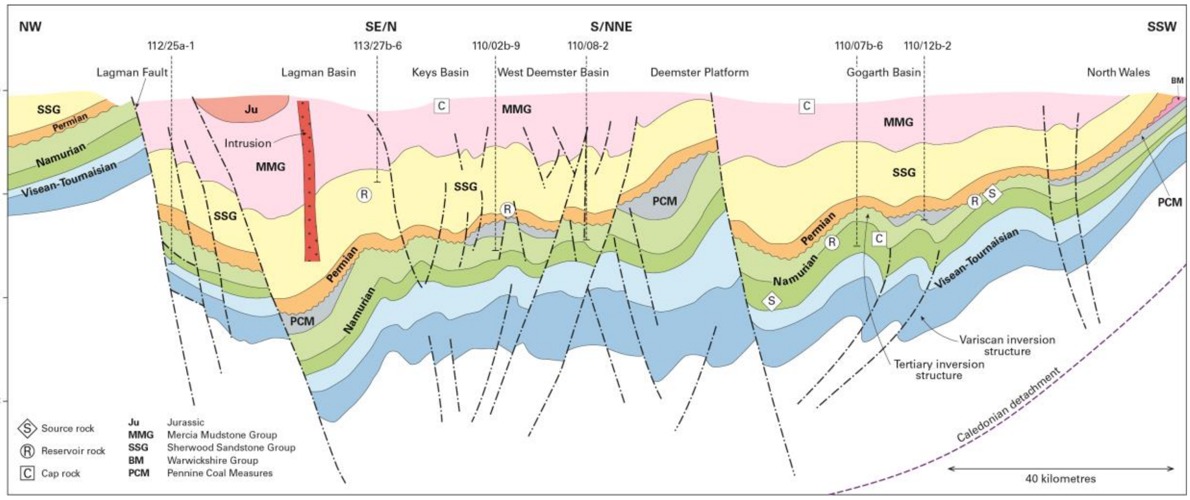


Figure 34 Synoptic cartoon to illustrate principal elements of the hydrocarbon system from the Lagman Fault (north) to the Welsh margin (south) of the East Irish Sea Basin

5.4 WESTERN MARGIN

The western margin of the East Irish Sea Basin comprises the Quadrant 109 Platform, and its extension beneath a thin Permo-Triassic cover into the Eubonia Basin. According to Jackson et al. (1995), the Quadrant 109 Syncline is a major, broad open fold with a SW-NE axial trace containing perhaps 5-6 km of Carboniferous rocks (Figures 35, 55). Shallow BGS boreholes have proved Westphalian strata on the southern limb. Namurian sequences are encountered on both limbs. Towards the south, the complementary Quadrant 109 Arch comprises a series of minor anticlines and synclines displaced by cross-faults (Figure 5). At the southern end of the seismic line illustrated in Figure 35, the arch appears to be dominated by a Variscan inversion anticlinal fold-thrust couple, with northward vergence. On this seismic line (and others in the area, e.g. Figures 36, 37) the northern, faulted limb of the syncline, including the Namurian-Westphalian strata described above, is poorly imaged, but there are hints of relatively steep dips on the NW side of the fault. In the interpretations presented, a significant component of syndepositional growth is inferred on the southern side of the fault, so that approaching 2.5 s TWTT of Carboniferous strata (c. 6 km) are preserved (Figure 36). Namurian and Westphalian strata, recognised by characteristic patterns of reflectivity, are overlain by a thick, less reflective package (comparable to that of the Whitehaven Sandstone of Cumbria), here inferred to belong to the Warwickshire Group (late Westphalian-Stephanian). The preferred interpretation of this structure is that it represents an extensional half-graben, a predominantly northward-dipping tilt-block. It is interesting to note a change in seismic character in the inferred Visean section updip towards the Quadrant 109 Arch, which may reflect development of reefal structures towards the top of the tilt-block, comparable to those in equivalent-age strata of the Bowland Fells onshore. There is only one well in the region, 109/05-1 which proved 361 m of Pennine Lower Coal Measures overlying 430 m of Millstone Grit.

The axis of the Quadrant 109 Syncline extends eastward beyond the discordant Eubonia Fault, beneath the thin Permo-Triassic cover of the Eubonia Basin (Figures 36-38). A hangingwall anticline is present, apparently of Variscan age, as the fold is truncated by the Variscan Unconformity (Figure 38). The unconformity and overlying Permo-Triassic cover are gently folded by continued growth of the Variscan anticlines during a further phase of inversion, of presumed Cenozoic age. The Eubonia Fault itself is strongly curved, from a SW-NE trend where it links to the Lagman Fault, to a more northerly trend on the western side of the Eubonia Basin, following the Permo-Triassic trend. In the Ogham Inlier, between the Eubonia Basin and the Keys Fault, Coal Measures strata reappear beneath the Permo-Triassic cover, and are penetrated by the well 112/30-1, just missing the Warwickshire Group.

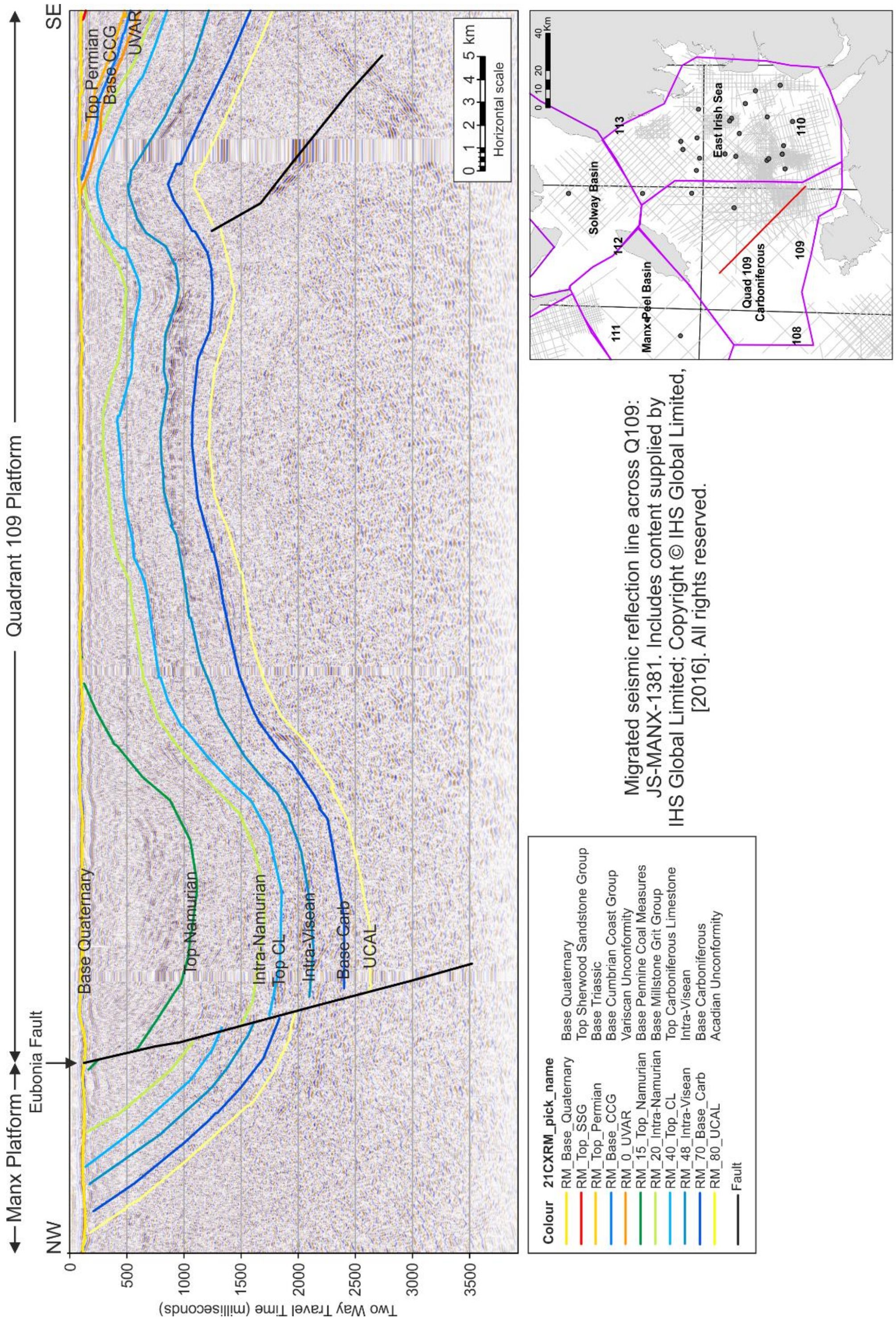


Figure 35 Migrated seismic reflection line across Q109: JS-MANX-138. Includes content supplied by IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

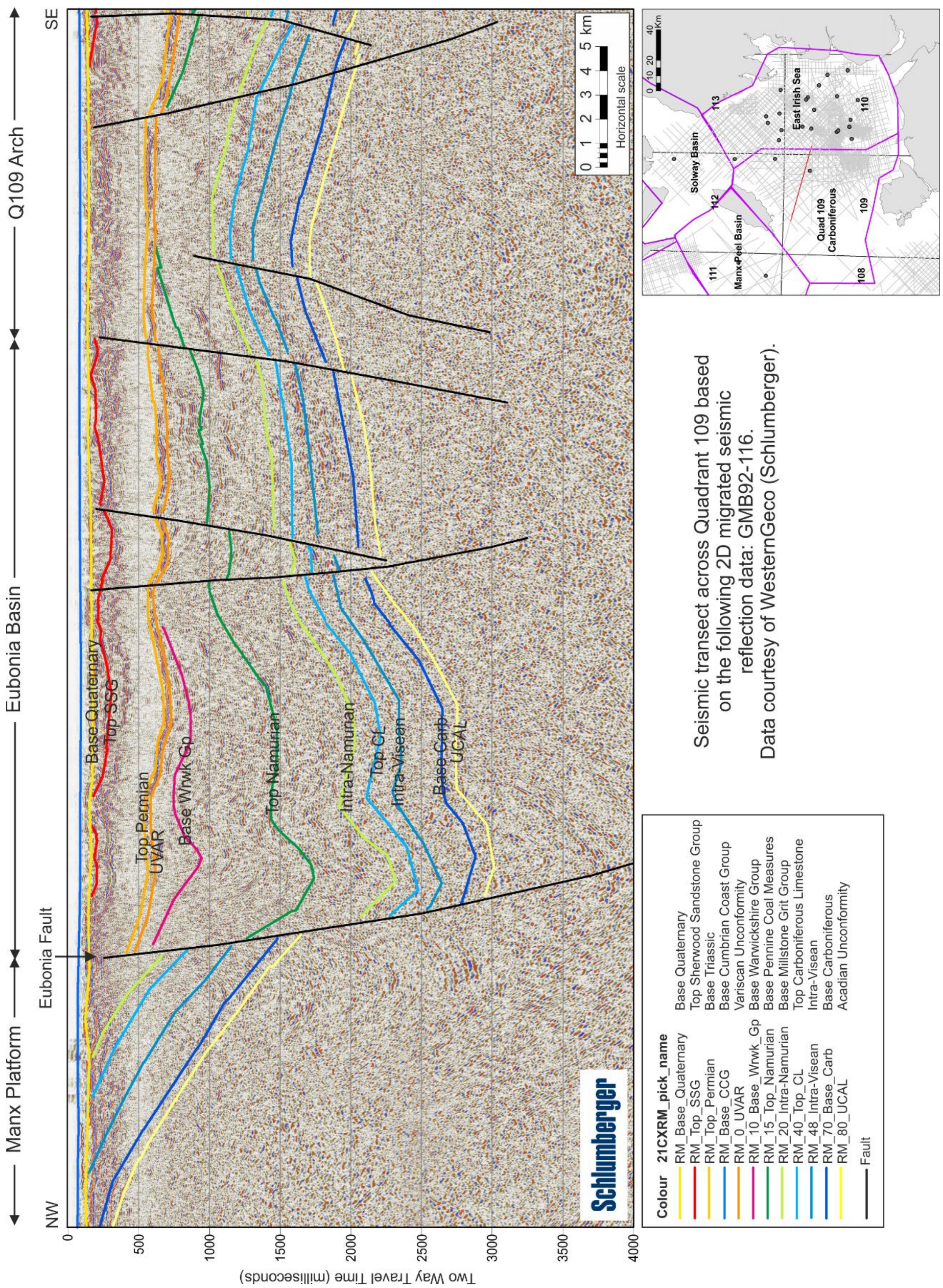


Figure 36 Seismic transect across Quadrant 109 based on the following 2D migrated seismic reflection data: GMB92-116. Data courtesy of WesternGeco (Schlumberger). Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

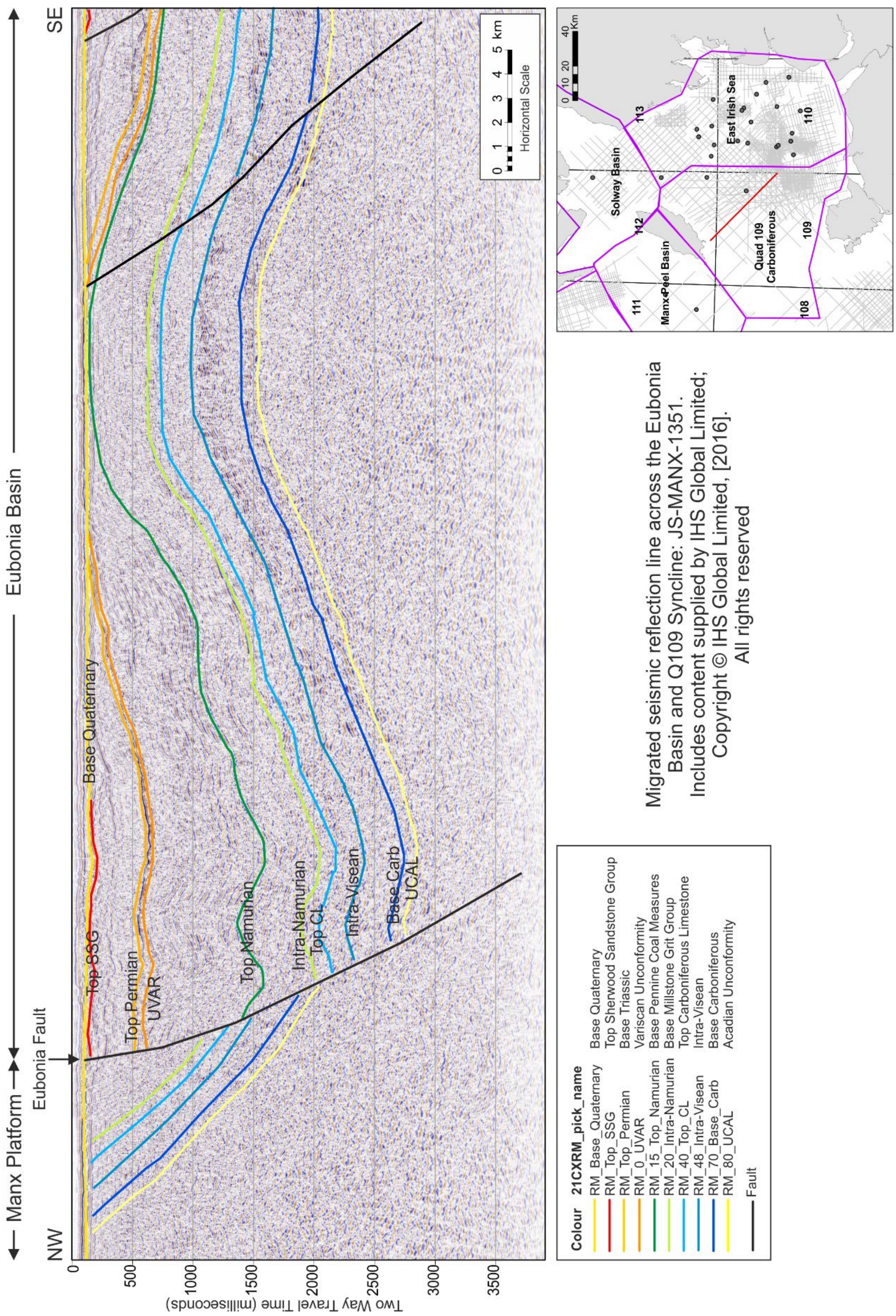


Figure 37 Migrated seismic reflection line across the Eubonia Basin and Quadrant 109 Syncline: JS-MANX-135. Includes content supplied by IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

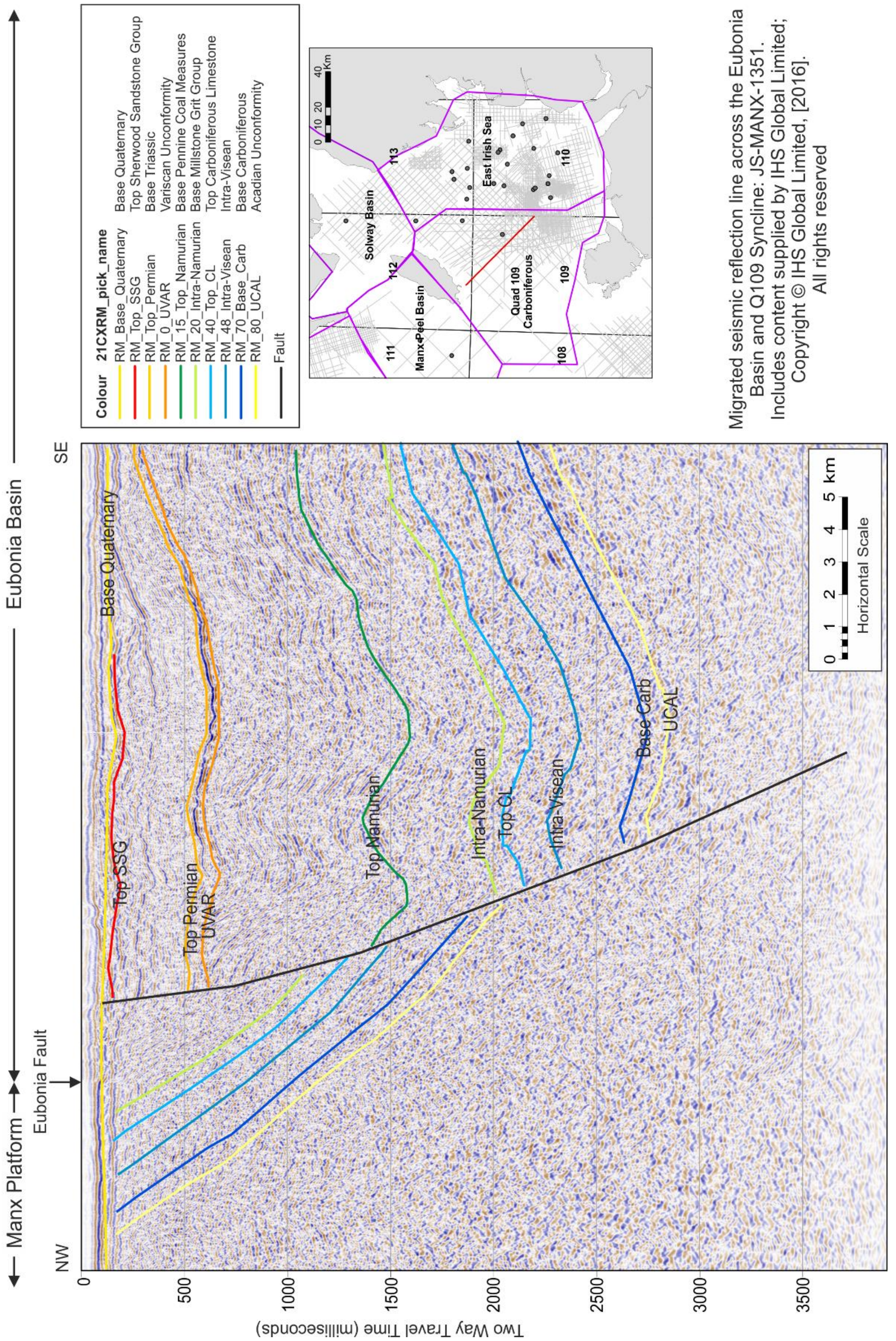


Figure 38 Detailed portion of Figure 37, part of migrated seismic reflection line across the Eubonia Basin and Quadrant 109 Syncline: JS-MANX-135. Includes content supplied by IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

Figure 39 illustrates key aspects of the hydrocarbon system in the Eubonia Basin and adjacent Quadrant 109 Arch. Note the development of inversion anticlines in response to Variscan compression, and further growth of these folds during Cenozoic inversion. Reservoir qualities of the late Carboniferous sandstones are uncertain. A good regional seal and caprock (Mercia Mudstone Group) is only locally present. Intraformational Carboniferous seals are untested.

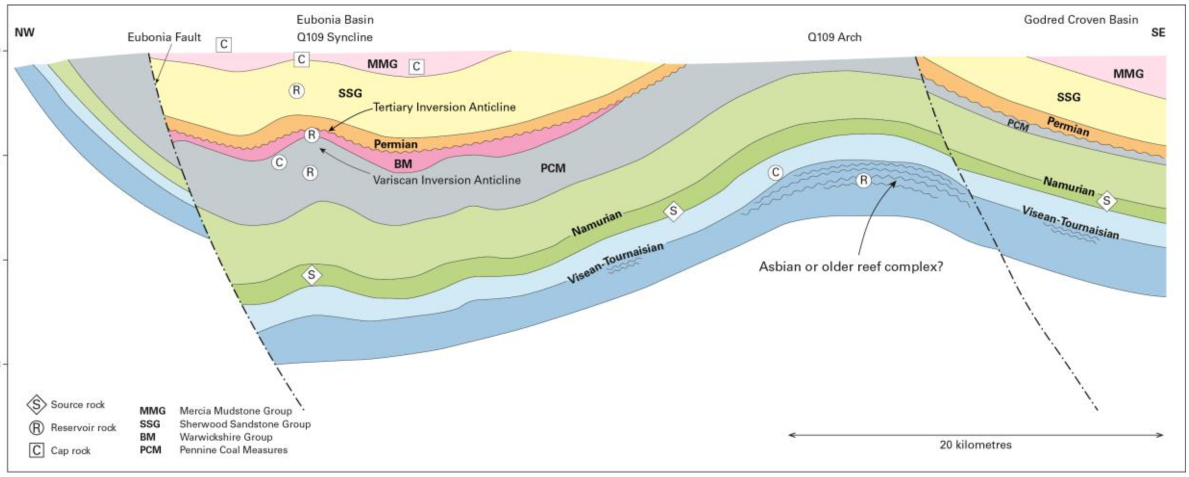


Figure 39 Synoptic cartoon to illustrate principal elements of the hydrocarbon system in the Eubonia Basin and Quadrant 109 Arch.

5.5 SOLWAY FIRTH BASIN

The Solway Firth Basin is a mildly asymmetrical sag basin, containing up to 3000 m of Permo-Triassic fill (Jackson et al., 1995). Two sections are presented, located at the eastern, Cumbrian, end of the basin (Figure 40), and farther west, across the depocentre of the basin (Figure 41). The Carboniferous strata are inferred to represent the infill of a basin originally continuous with the Northumberland Basin (Holliday et al., 1991). Well 112/15-1, proved Yoredale Group strata of Pendleian or late Brigantian age (see Wakefield et al., 2016). The principal seismic picks within the basin lie at the top of a reflective package, here inferred to be the Fell Sandstone (Middle Border Group), although this is unconfirmed by drilling. Overlying this is a less reflective sequence of presumed late Visean strata and then a reflective sequence correlated with the Millstone Grit Group. Pennine Coal Measures, formerly worked in the Cumberland Coalfield, both onshore and up to 5 miles out beneath the sea, are interpreted to be overlain by the Whitehaven Sandstone, a Warwickshire Group equivalent. The later Carboniferous strata are only preserved on the southern side of the basin (Figures 40, 42) adjacent to the Maryport Fault. Along the northern and central parts of the basin, the Coal Measures have been largely eroded, reflecting the presence of a Variscan axis of inversion. On the northern margin of the basin, the North Solway Fault was syndepositionally active during Carboniferous time (Deegan, 1973). The Maryport Fault, bounding the Manx-Lake District Ridge on its northern side (Figure 40), has a long and interesting history of reactivation (Chadwick et al., 1993). Cenozoic inversion along this zone resulted in compressional reactivation of original Variscan structures. The Stranraer Basin (Figure 5) is a half-graben tilted NE towards the Loch Ryan Fault, and is effectively a satellite of the Solway Firth Basin. The fault has a throw estimated at 1525 to 1700 m (Kelling and Welsh, 1970), and has controlled deposition in Triassic, Permian and (possibly) in Carboniferous time. It appears to have initiated from a dextral, wrench fracture within the

Caledonian basement (Kelling and Welsh, 1970). None of the project seismic data enters the Stranraer Basin so it is not considered in further detail.

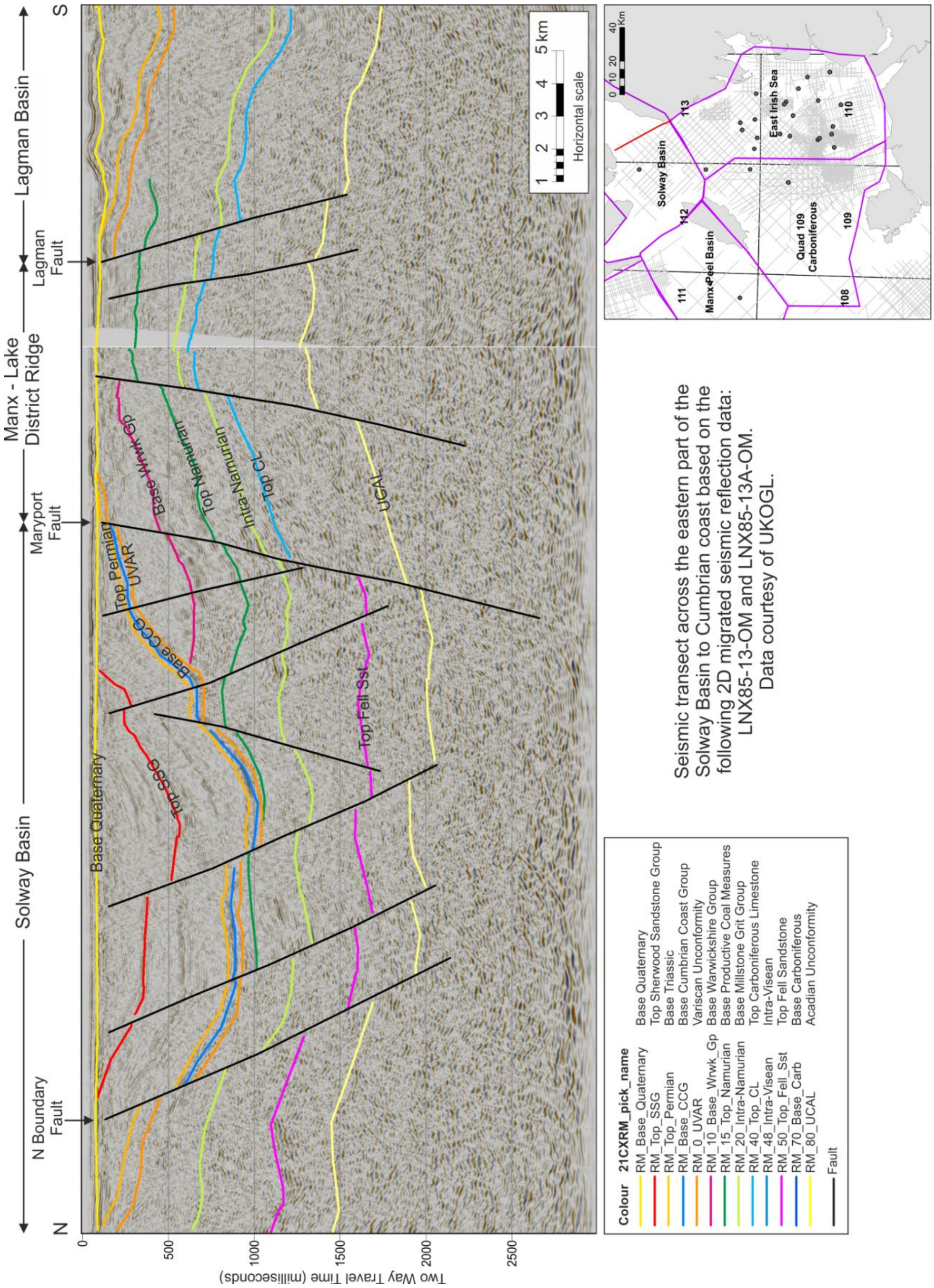


Figure 40 Seismic transect across the eastern part of the Solway Basin to Cumbrian coast based on the following 2D migrated seismic reflection data: LNX85-13-OM and LNX85-13A-OM. Data courtesy of UKOGL. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

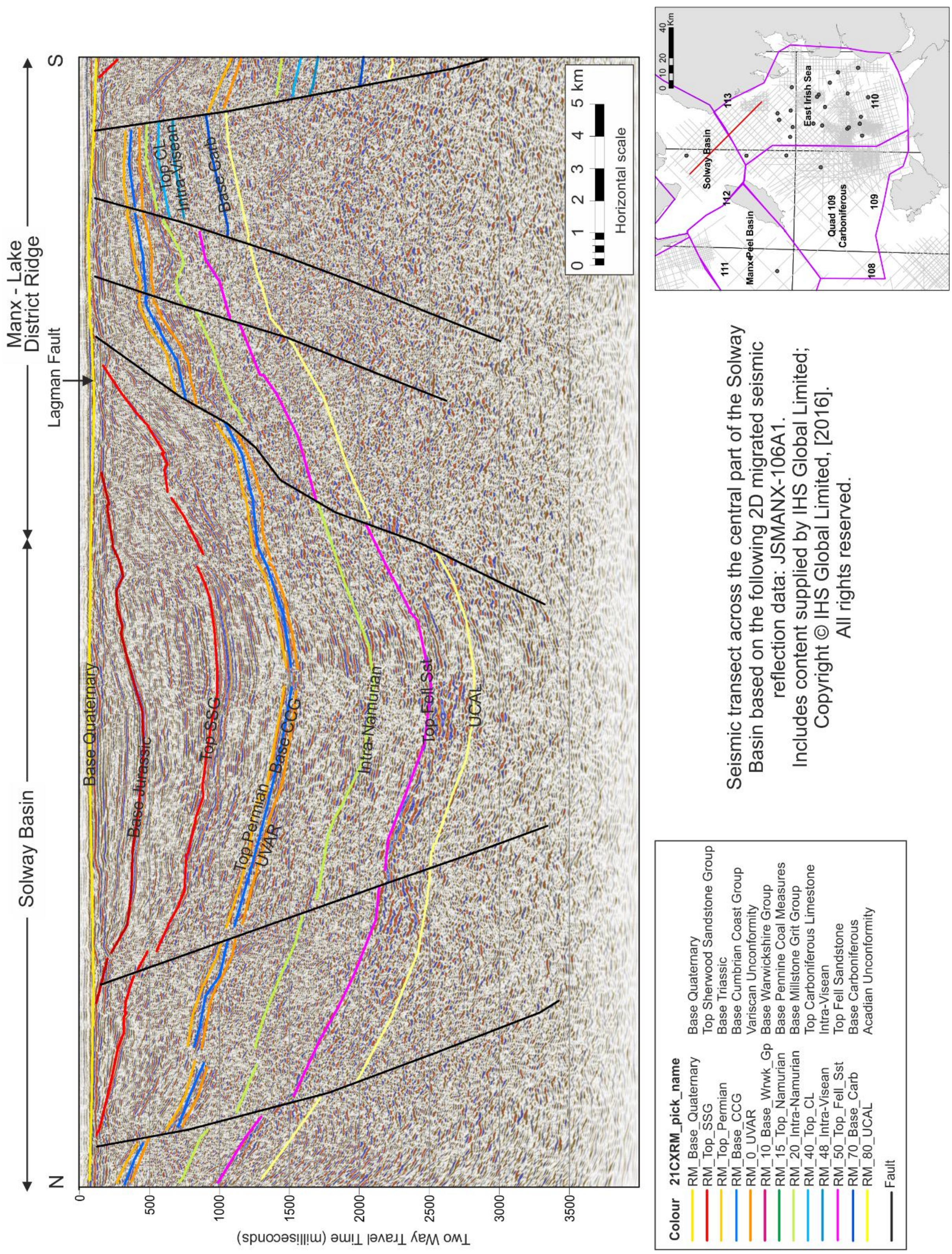


Figure 41 Seismic transect across the central part of the Solway Basin based on the following 2D migrated seismic reflection data: JSMANX-106A1. Includes content supplied by IHS Global Limited; Copyright © IHS Global Limited, [2016]. All rights reserved. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

Figure 42 illustrates key aspects of the hydrocarbon system along a north-south transect across the eastern part of the Solway Firth Basin. The northward extent of the high quality Bowland Shale source rock is uncertain and likely replaced by the laterally equivalent shales and coals in the Scremerston Formation and Yoredale Group (see also Figure 59). Reservoir qualities of the late Carboniferous sandstones are uncertain. Note the Variscan axis of inversion, on the northern side of the basin, directly overlain by the Permian-Mesozoic sag basin, in which a good regional seal and caprock (Mercia Mudstone Group) is present. Cenozoic inversion is focussed on the Ramsey-Whitehaven Ridge.

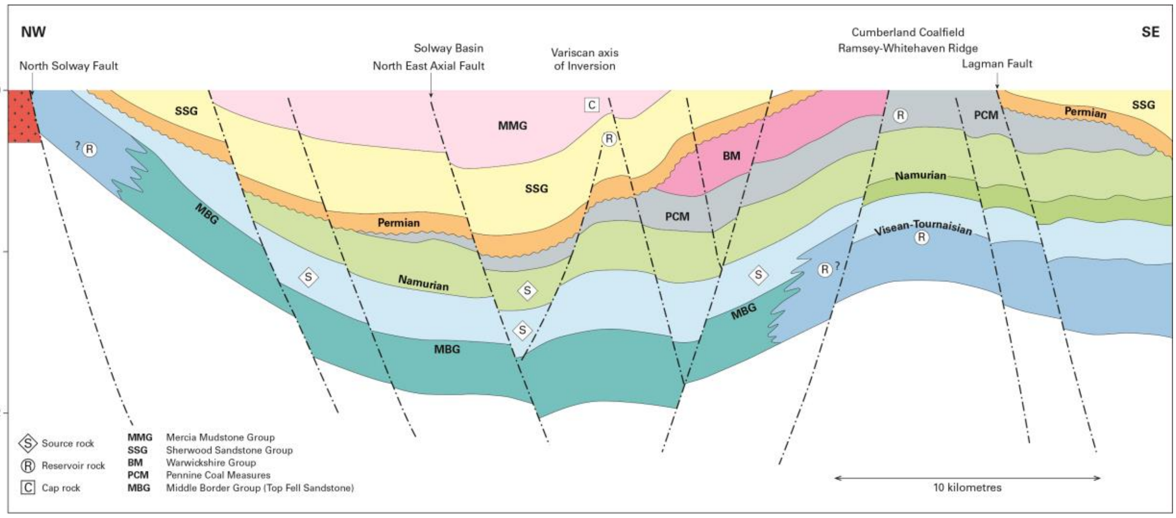


Figure 42 Synoptic cartoon to illustrate principal elements of the hydrocarbon system in the eastern part of the Solway Firth Basin

Figure 43 illustrates key aspects of the hydrocarbon system along a north-south transect across the western part of the Solway Firth Basin. The Bowland Shale is likely absent and replaced by coals and shales in the Scremerston Formation and Yoredale Group. Reservoir qualities of the late Carboniferous sandstones are uncertain, and even more speculative in the Visean carbonates. Note the Variscan axis of inversion, on the northern side of the basin, directly overlain by the Permian-Mesozoic sag basin, in which a good regional seal and caprock (Mercia Mudstone Group and locally Lias) is present. Cenozoic inversion is focussed on the Ramsey-Whitehaven Ridge.

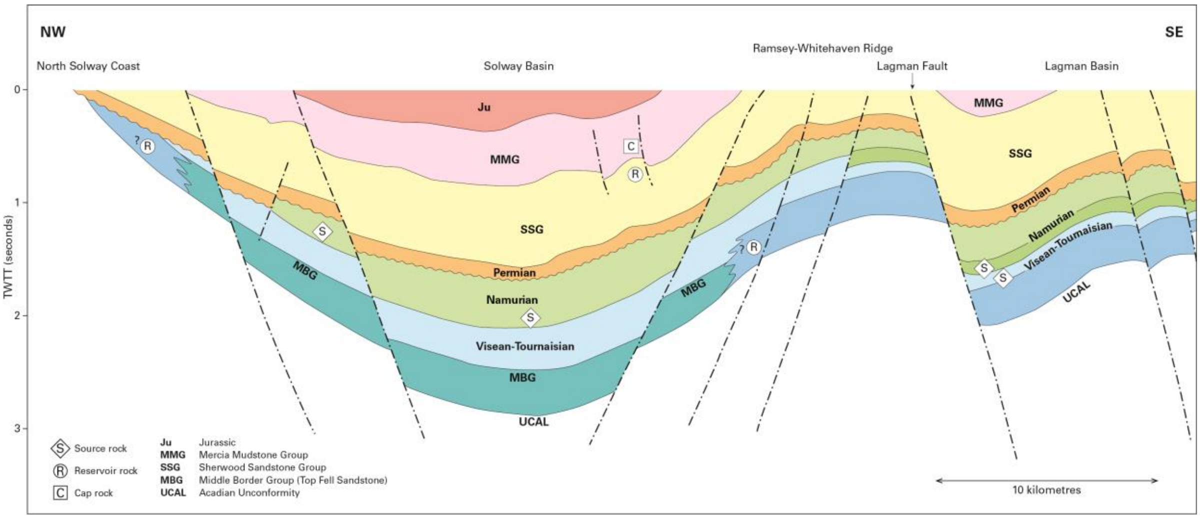


Figure 43 Synoptic cartoon to illustrate principal elements of the hydrocarbon system in the western part of the Solway Firth Basin

5.6 PEEL BASIN

The Peel Basin is an assymetrical half-graben, with the principal controlling faults on the northern side of the basin (Figures 44, 45). The oldest strata in the basin may be the red-bed strata of the Peel Group, which occur within a fault-bounded basin on the west coast of the Isle of Man (Piper and Crowley, 1999). They may represent very early syn-rift deposits of Devonian age, or late Carboniferous molasse-type sediments (Quirk et al., 1999; Chadwick et al., 2001). Two boreholes (111/29-1, 111/25-1a) penetrate Permian, Triassic and Jurassic strata, and enter Visean carbonate platform strata preserved in a series of tilt-blocks (Figures 44, 45). The Permian sequence is thin and unlikely to provide an effective seal, but the Mercia Mudstone Group provides a good regional caprock. The basin lies within the hangingwall block of the WNW-dipping Barrule Thrust Zone, a Caledonian compressional basement structure reactivated subsequently, which is well imaged by the seismic sections (Figure 45). The late Carboniferous sequence is interpreted to have been almost completely removed by post-Variscan inversion. A small relic of Namurian strata is present on the southern side of the basin, close to the Isle of Man (Figure 46). The Permo-Triassic sequence exceeds 2000 m in the centre of the basin, slightly less than the Solway Firth Basin. The Mercia Mudstone Group contains thin lenses of Jurassic strata, incorporated within a complex mosaic of ‘mini-basins’ (Figure 46) by a combination of detachment (from the Sherwood Sandstone Group sub-strate), halokinesis, ‘rift-raft-tectonics’ (Penge et al., 1999; Newman, 1999) and finally, the intrusion of Cenozoic dykes and sills.

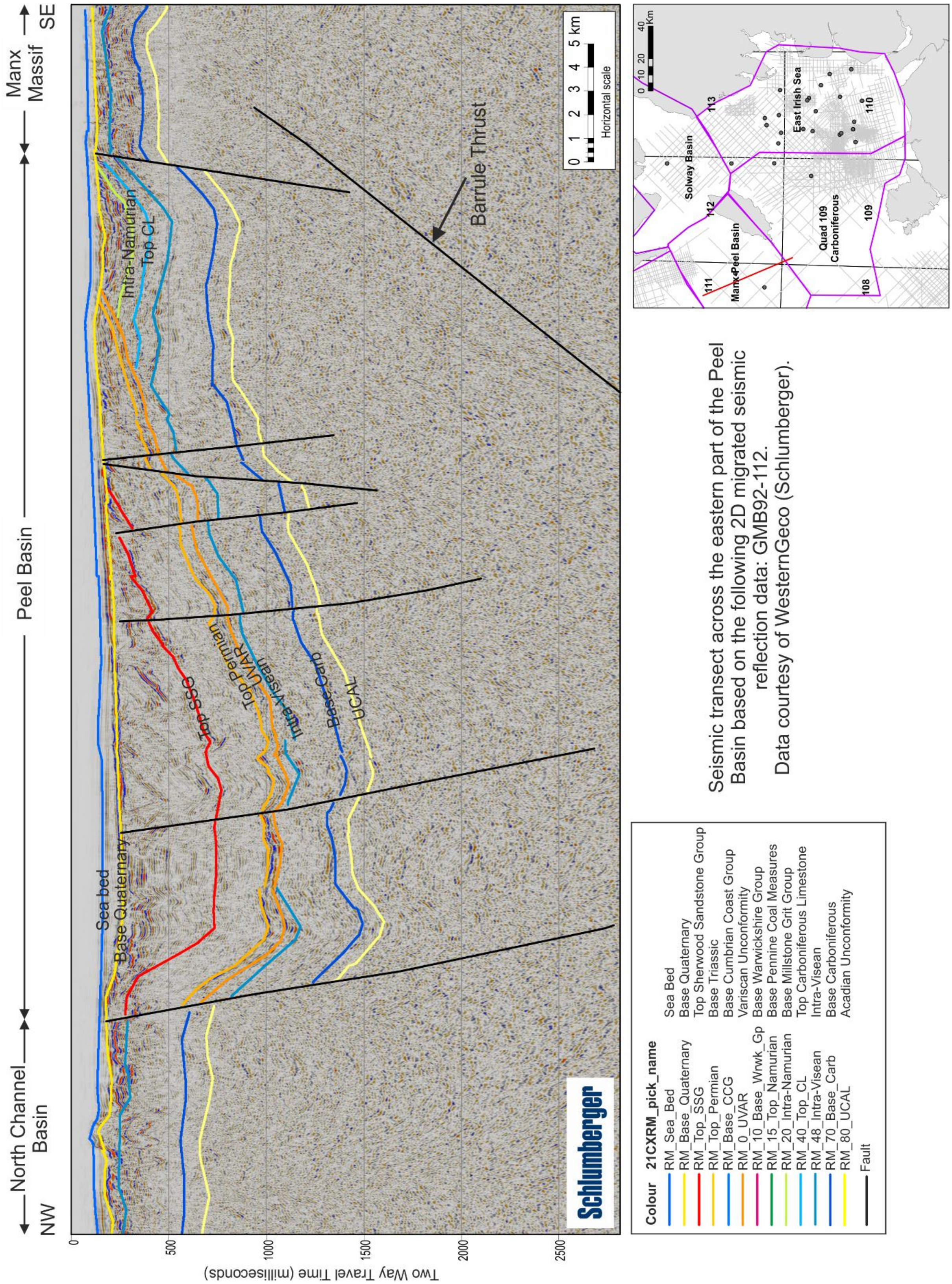


Figure 44 Seismic transect across the eastern part of the Peel Basin based on the following 2D migrated seismic reflection data: GMB92-112. Data courtesy of WesternGeco (Schlumberger). Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

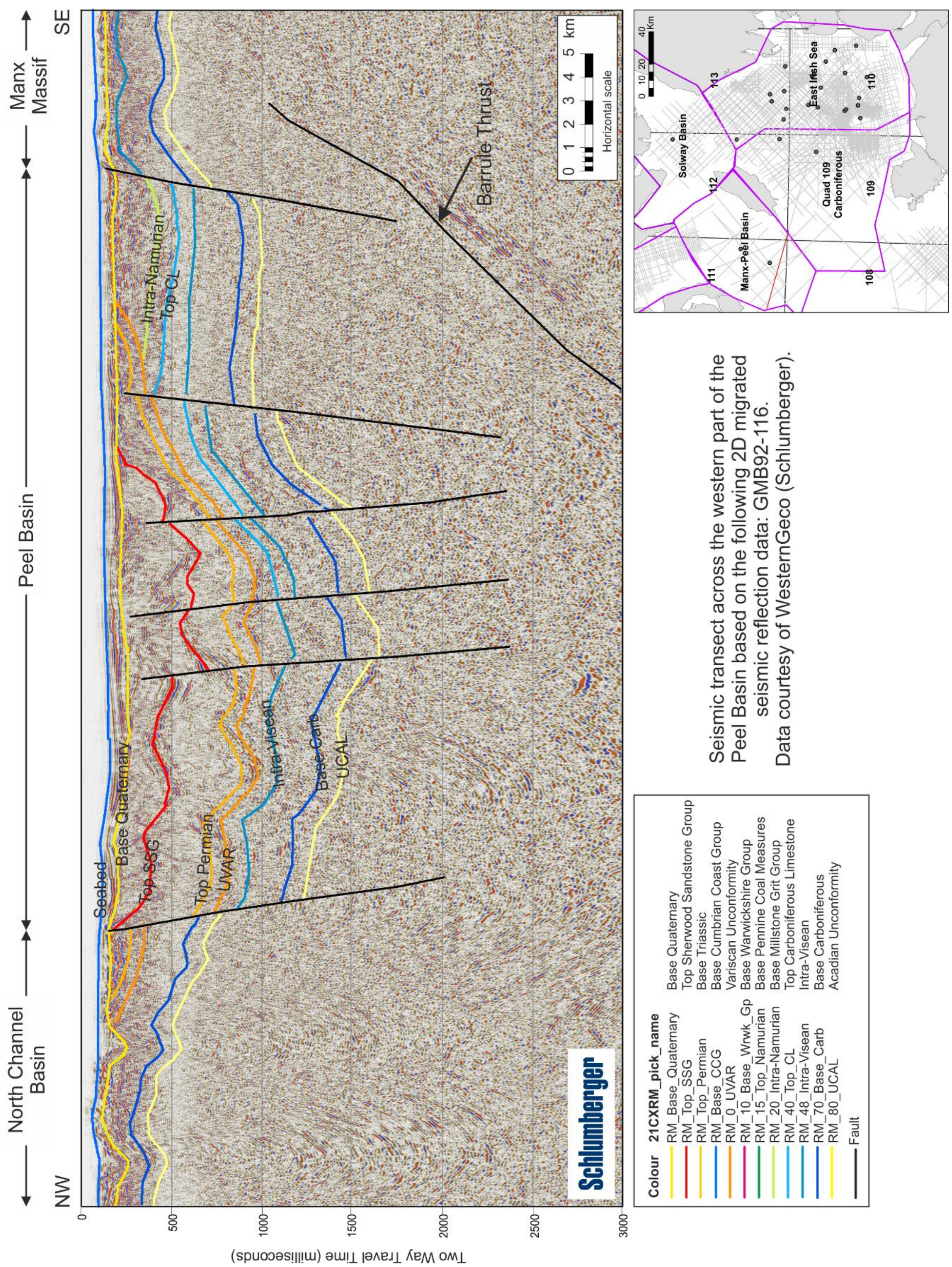


Figure 45 Seismic transect across the western part of the Peel Basin based on the following 2D migrated seismic reflection data: GMB92-116. Data courtesy of WesternGeco (Schlumberger). Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

Figure 46 illustrates key aspects of the hydrocarbon system along a north-south transect across the eastern part of the Peel Basin. Potential Namurian source rocks have been removed following Variscan inversion, except for a narrow strip along the southern edge of the basin, adjacent to the Isle of Man. Reservoir qualities of the Visean carbonates are uncertain. Note the Variscan axis of inversion, on the northern side of the basin, directly overlain by the Permian-Mesozoic sag basin, in which a good regional seal and caprock (Mercia Mudstone Group, and locally Lower Jurassic) is present.

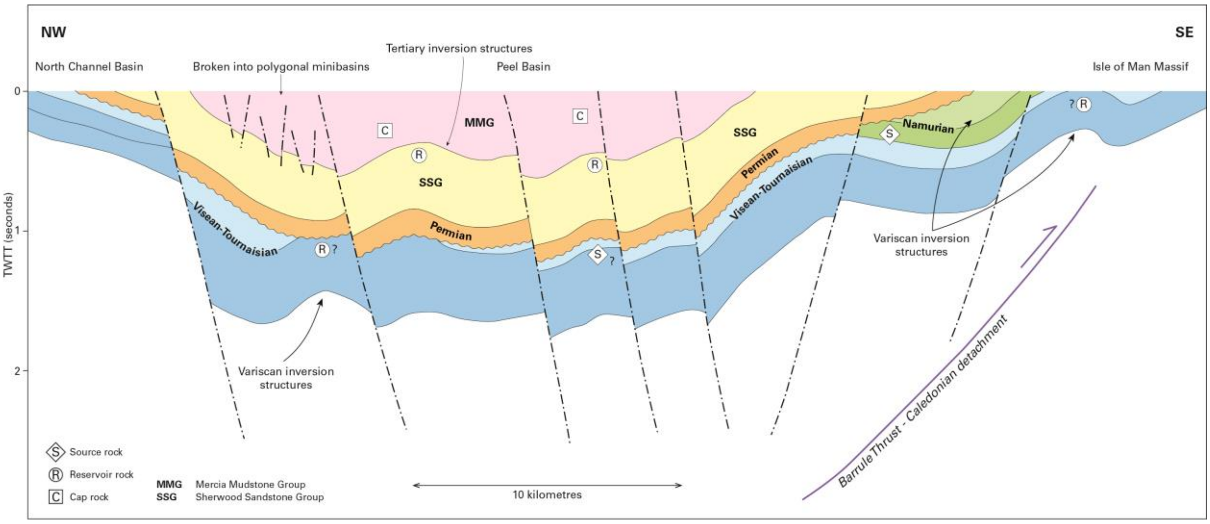


Figure 46 Synoptic cartoon to illustrate principal elements of the hydrocarbon system in the Peel Basin

5.7 NORTH CHANNEL – CLYDE BASINS

A detailed analysis of the component basins of the North Channel basin system, i.e the Portpatrick Sub-basin, and the Larne Basin, was the subject of a confidential report by Quinn (2008). Both of these are predominantly Permo-Triassic basins that form a major rift through the Southern Uplands Massif. Only one well (111/15-1) penetrated the Permian in these offshore basins, entering the early Palaeozoic through a faulted contact at the southern margin of the massif. Both Quinn (2008) and this study regard it unlikely (on seismic evidence) that Carboniferous strata underlie the southern part of the basin, even though they are probably present in other nearby re-entrants into the massif (Stranraer and Strangford Lough). On the other hand (Jackson et al., 1995; Fig. 22) and N.J.P.Smith (pers. comm., 2016) favour the presence of a thin (<400 m) Carboniferous succession. In the Northern Ireland onshore, deep boreholes at Ballytober and Cairncastle in the Larne Basin, and Portmore in the Rathlin Basin, penetrated Carboniferous sequences (Reay, 2004, Fig. 22.9). Carboniferous strata are more likely present to north of the Southern Uplands Fault, within the Midland Valley basins. Shallow BGS boreholes prove that Coal Measures extend westward from the onshore in Ayrshire towards the South West Arran Trough. Interpretation of the Carboniferous sequence on Figure 47 is highly interpretive and low confidence, as a consequence of the absence of well data. In addition a very limited amount of seismic data were interpreted. The base of the Clyde Plateau lavas provide an intra-early Carboniferous pick, and indicate that a significant thickness of underlying Devonian strata may be present.

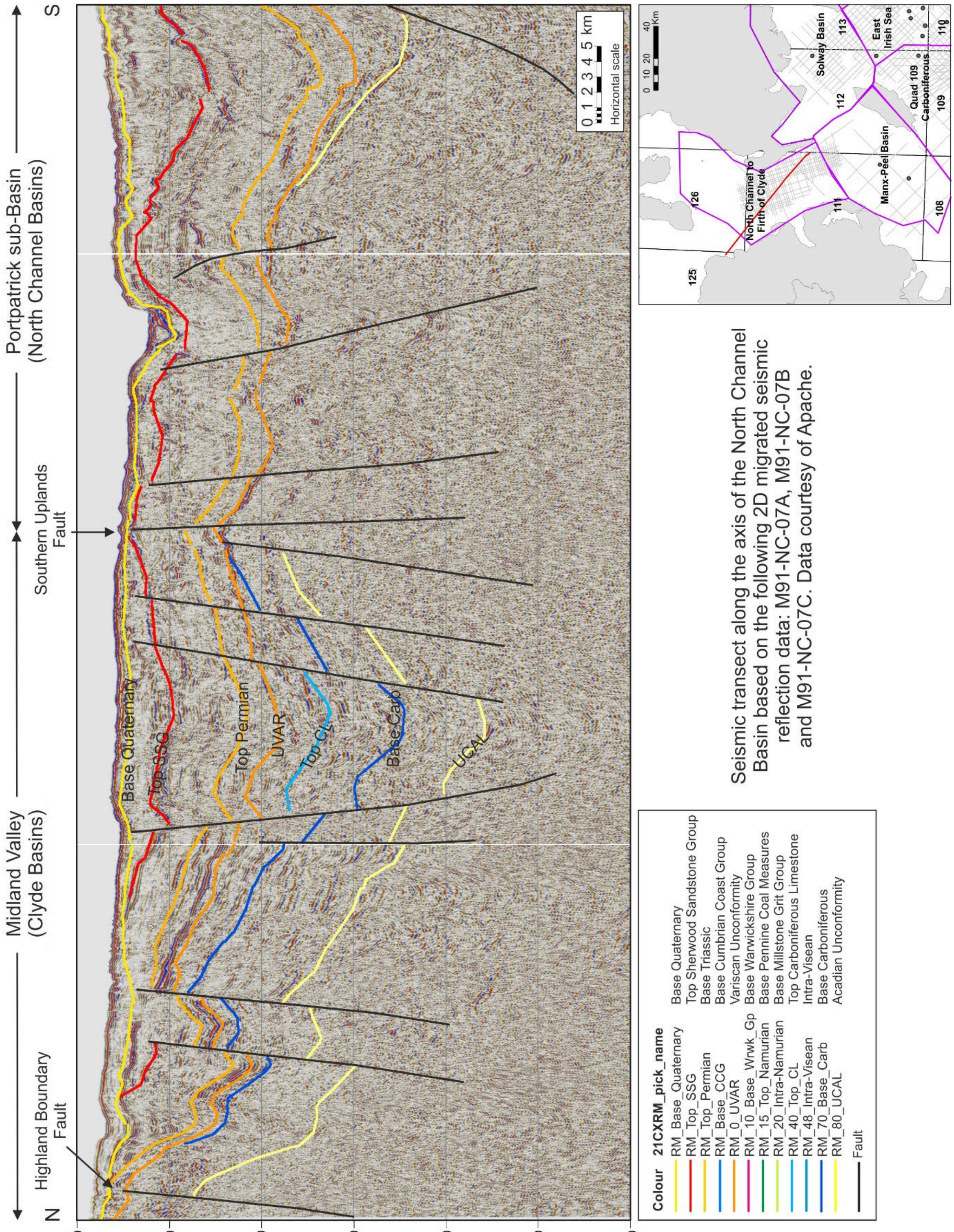


Figure 47 Seismic transect along the axis of the North Channel Basin based on the following 2D migrated seismic reflection data: M91-NC-07A, M91-NC-07B and M91-NC-07C. Data courtesy of Apache. Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

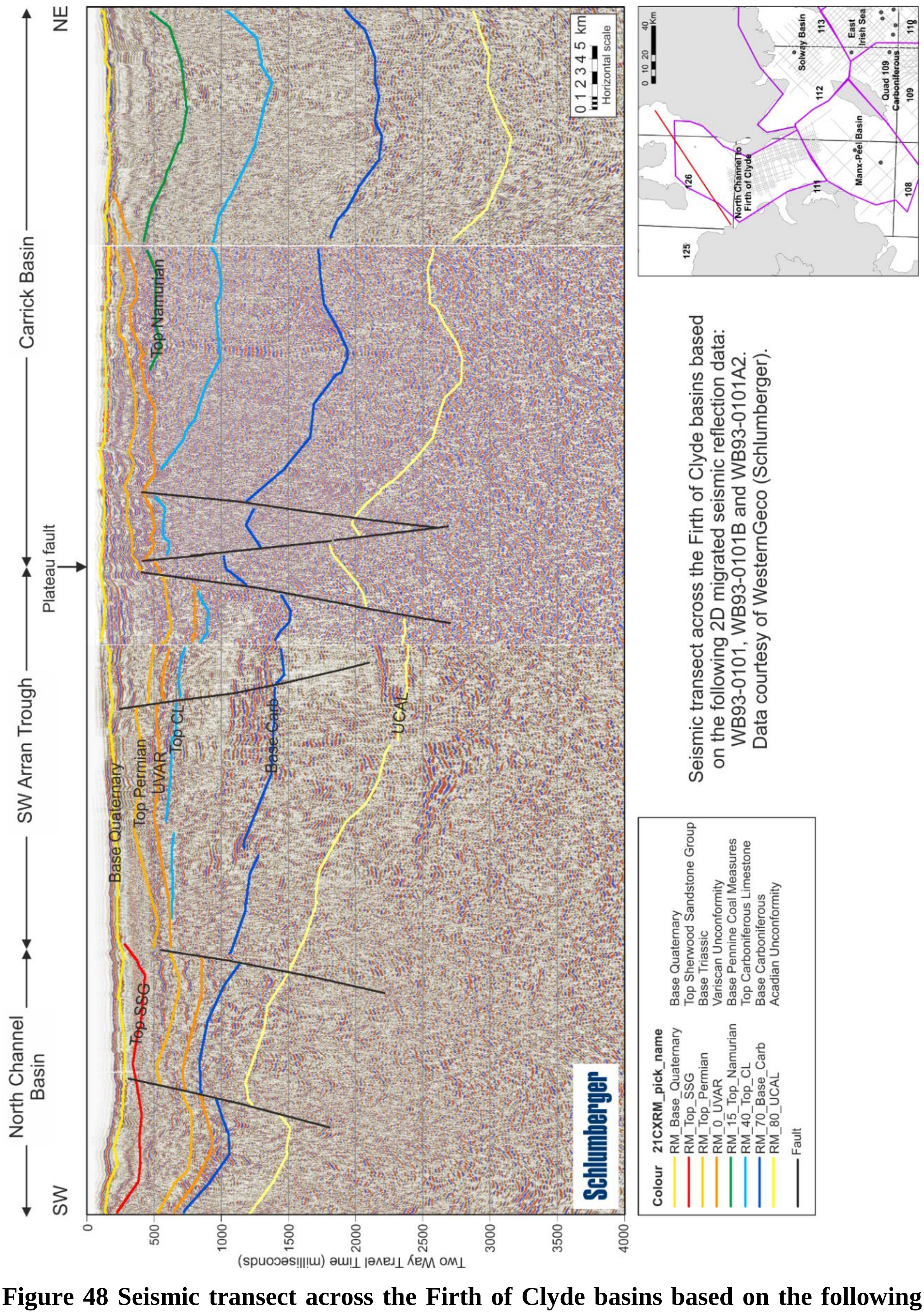


Figure 48 Seismic transect across the Firth of Clyde basins based on the following 2D migrated seismic reflection data: WB93-0101, WB93-0101B and WB93-0101A2. Data courtesy of WesternGeco (Schlumberger). Note that whilst not all picked intervals are of distinct reflectivity throughout any particular line, the use of a large quantity of surrounding data enables coherent regional interpretation.

5.8 SUMMARY OF BASIN EVOLUTION

Based on the seismic interpretation described above, the following events can be interpreted:

- Early Devonian – Acadian deformation establishes Caledonide SW-NE grain
- Late Devonian – sinistral transtension, NNW-SSE aligned fracture system?
- Visean – extensional reactivation on Caledonide NE-SW trend, dextral strike-slip
- Late Westphalian – shortening on Variscide WSW-ENE trend
- Late Westphalian – uplift and erosion, Warwickshire Group deposition
- Stephanian – shortening on Uralide NNW-SSE trend, inversion on Keys Fault etc
- Permian – uplift and erosion, incipient rifting
- Triassic- strong W-E extension and rapid subsidence
- Jurassic – rifting continues, maximum burial, peak hydrocarbon generation
- Cretaceous - Late Cimmerian uplift?
- Cenozoic – magmatism, further hydrocarbon generation and Alpine inversion

5.9 STRUCTURE MAPS FOR KEY HORIZONS

A set of structure maps in depth (metres below sea level) derived from the depth converted maps in Pharaoh et al. (2016a) is presented here. It is important to note that the variable data quality and sparsity of deep wells leads to a seismic interpretation which is strongly driven by regional geological models, themselves heavily dependent on inference from the onshore area. This is particularly the case with the deeper Carboniferous horizons which are not penetrated by any well and which may be only weakly reflective. In such cases, picks from better quality data may be interpolated through areas with poor quality data, as a modelled surface, to ensure a continuous surface for gridding.

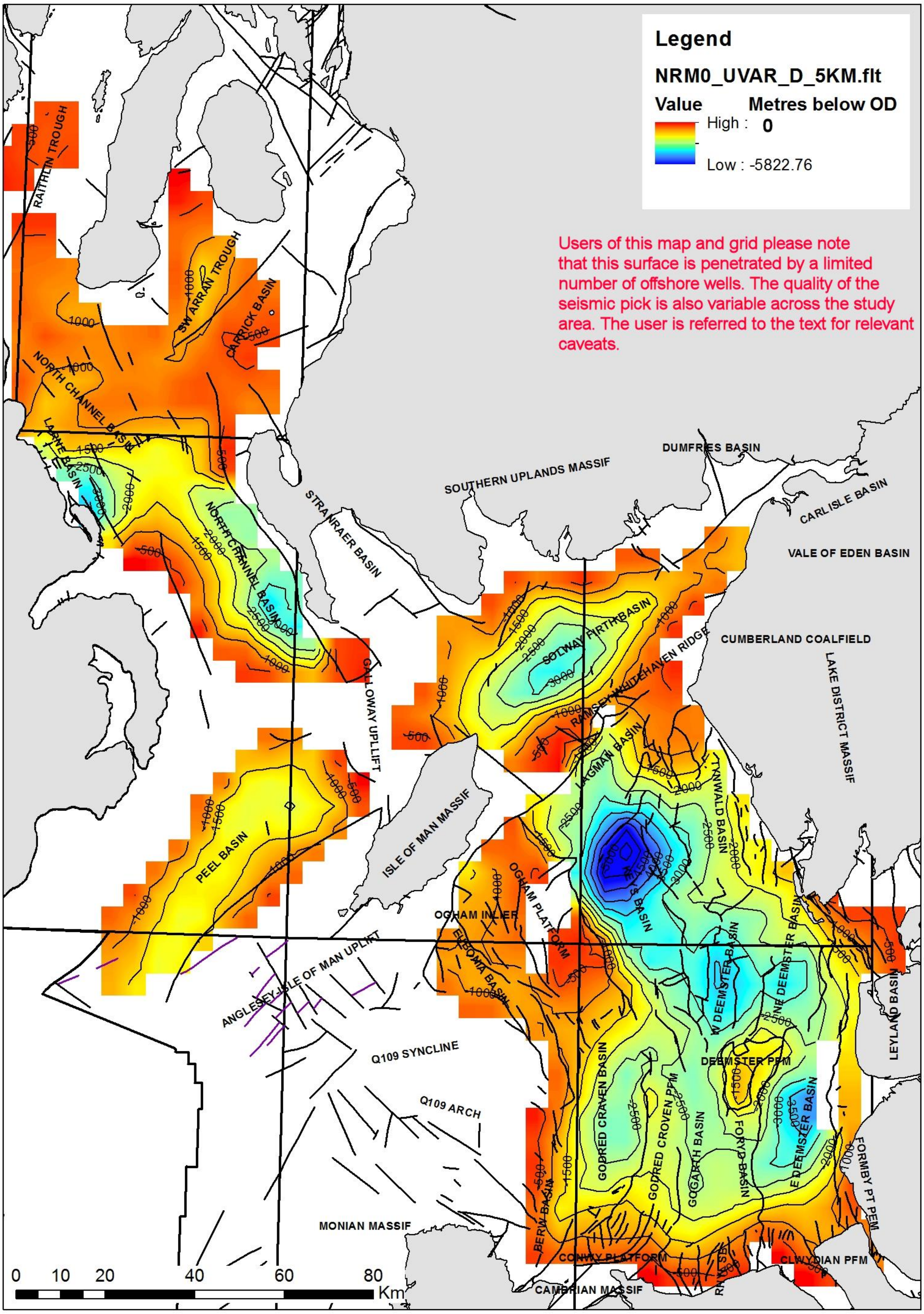


Figure 49 Structure map in depth (metres sub sea level) for the Variscan Unconformity.

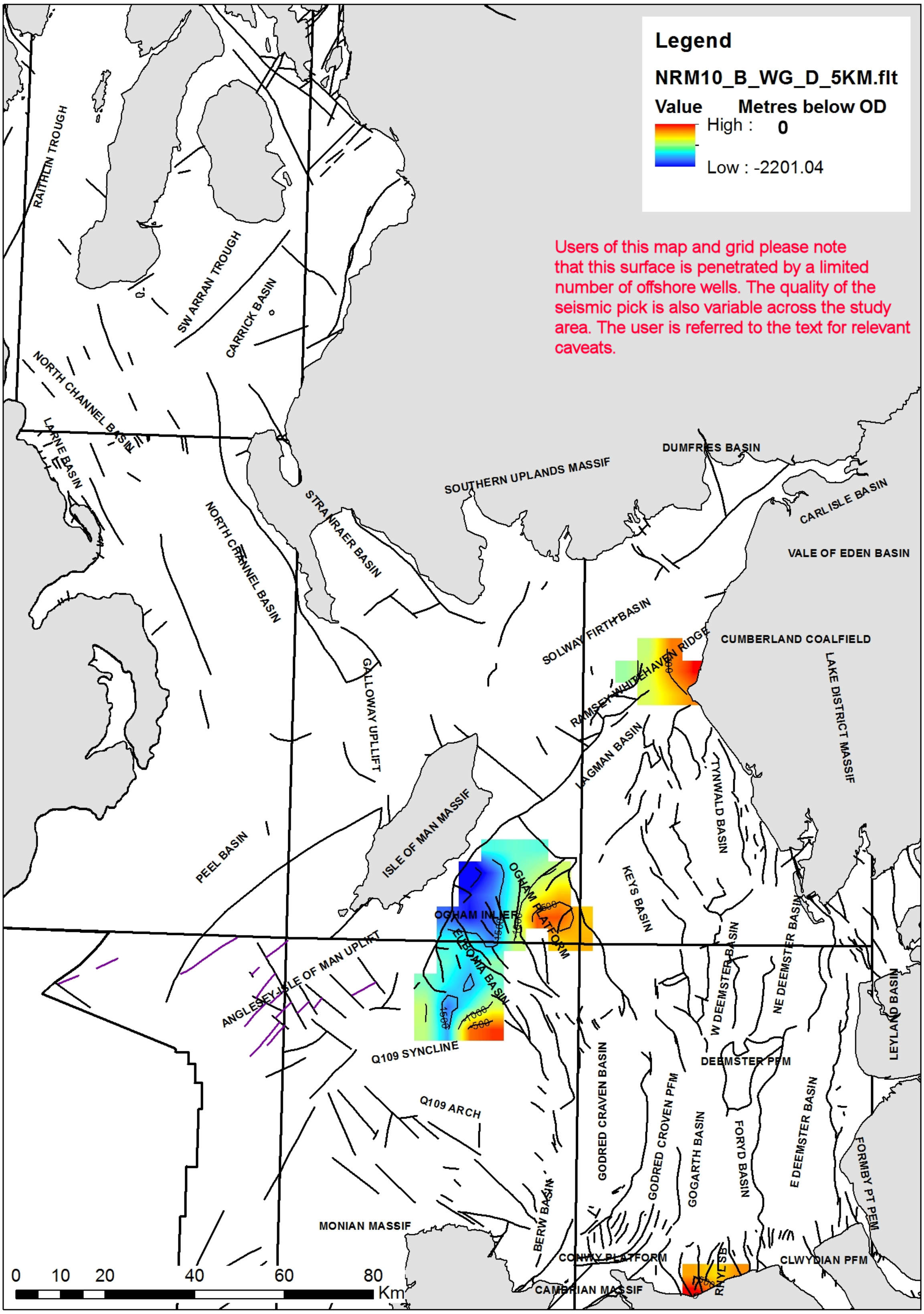


Figure 50 Structure map in depth (metres sub sea level) for the Base of the Warwickshire Group.

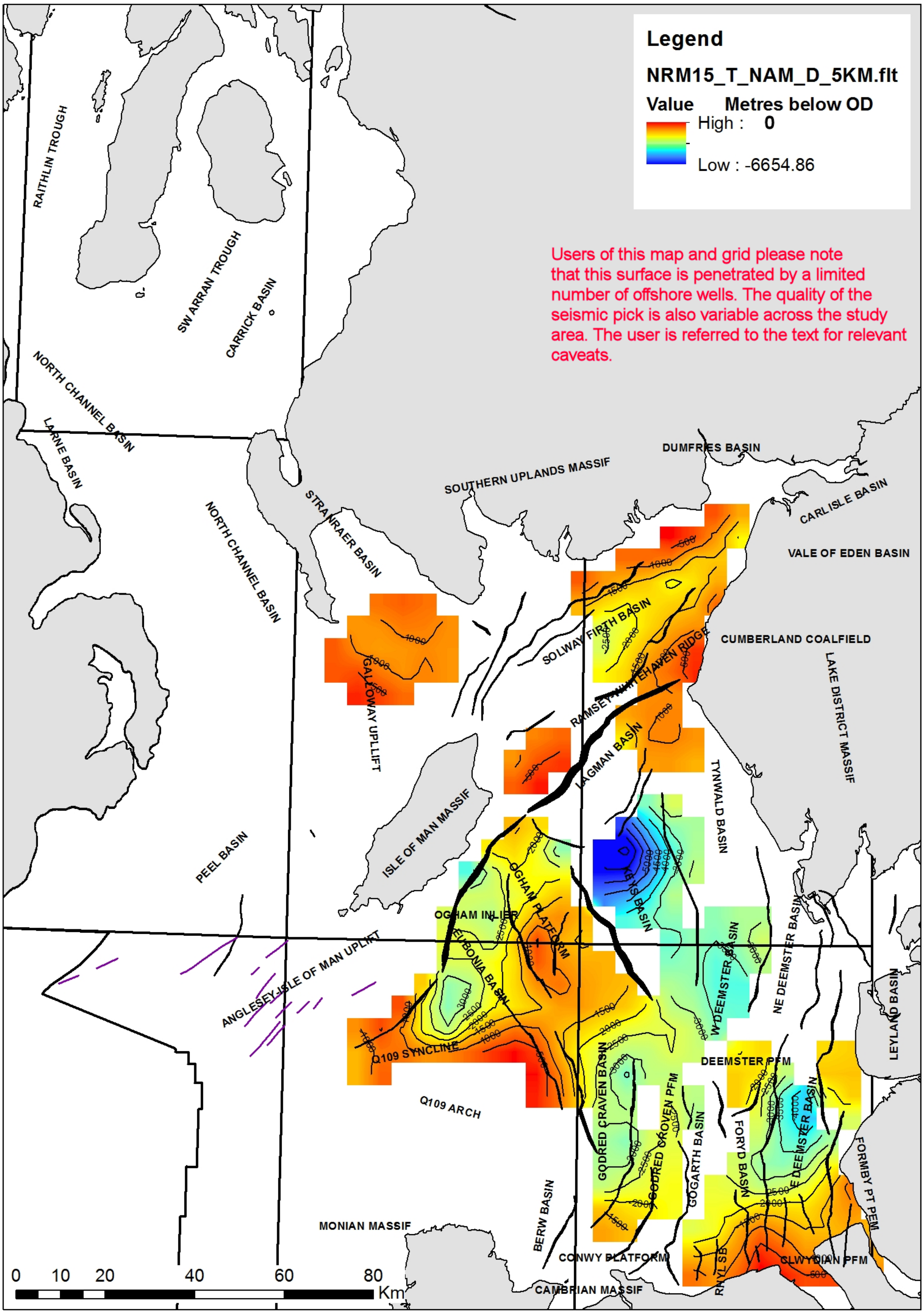


Figure 51 Structure map in depth (metres sub sea level) for the Top of the Namurian (Base Coal Measures) with simplified fault pattern for the Top Namurian.

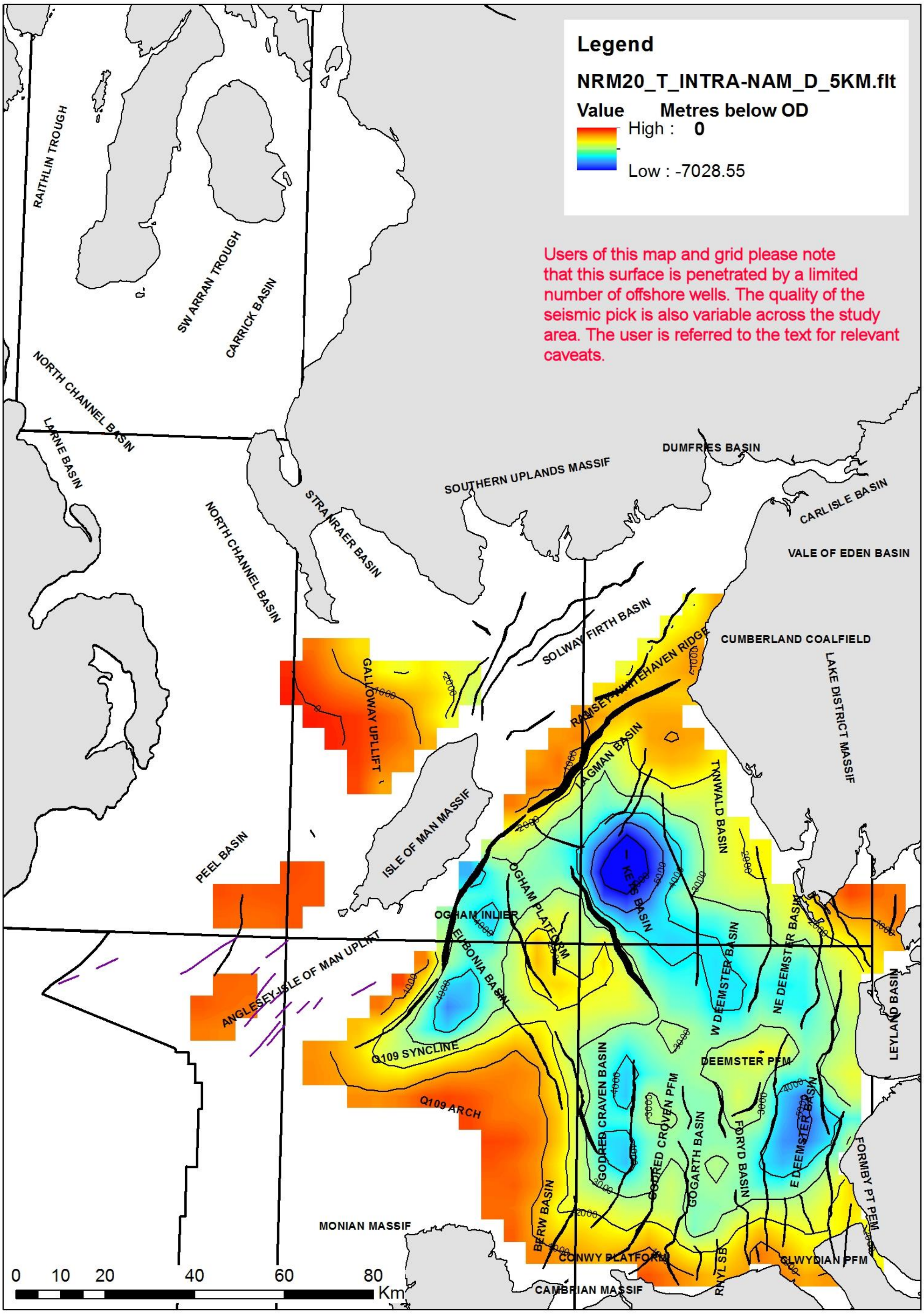


Figure 52 Structure map in depth (metres sub sea level) for the Intra-Namurian pick, equated with the base of the Millstone Grit Group.

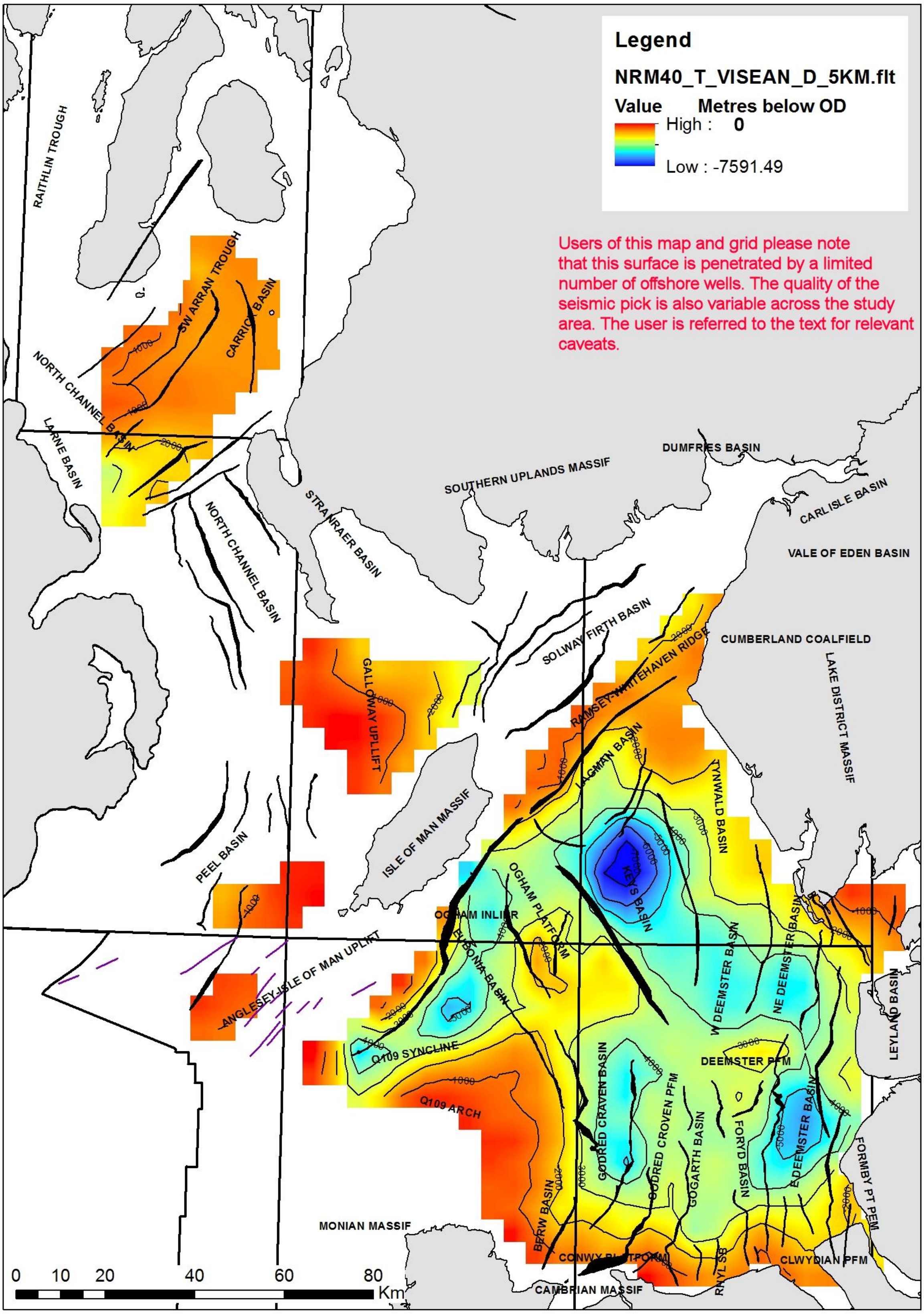


Figure 53 Structure map in depth (metres sub sea level) for the Top Visean (Carboniferous Limestone Supergroup).

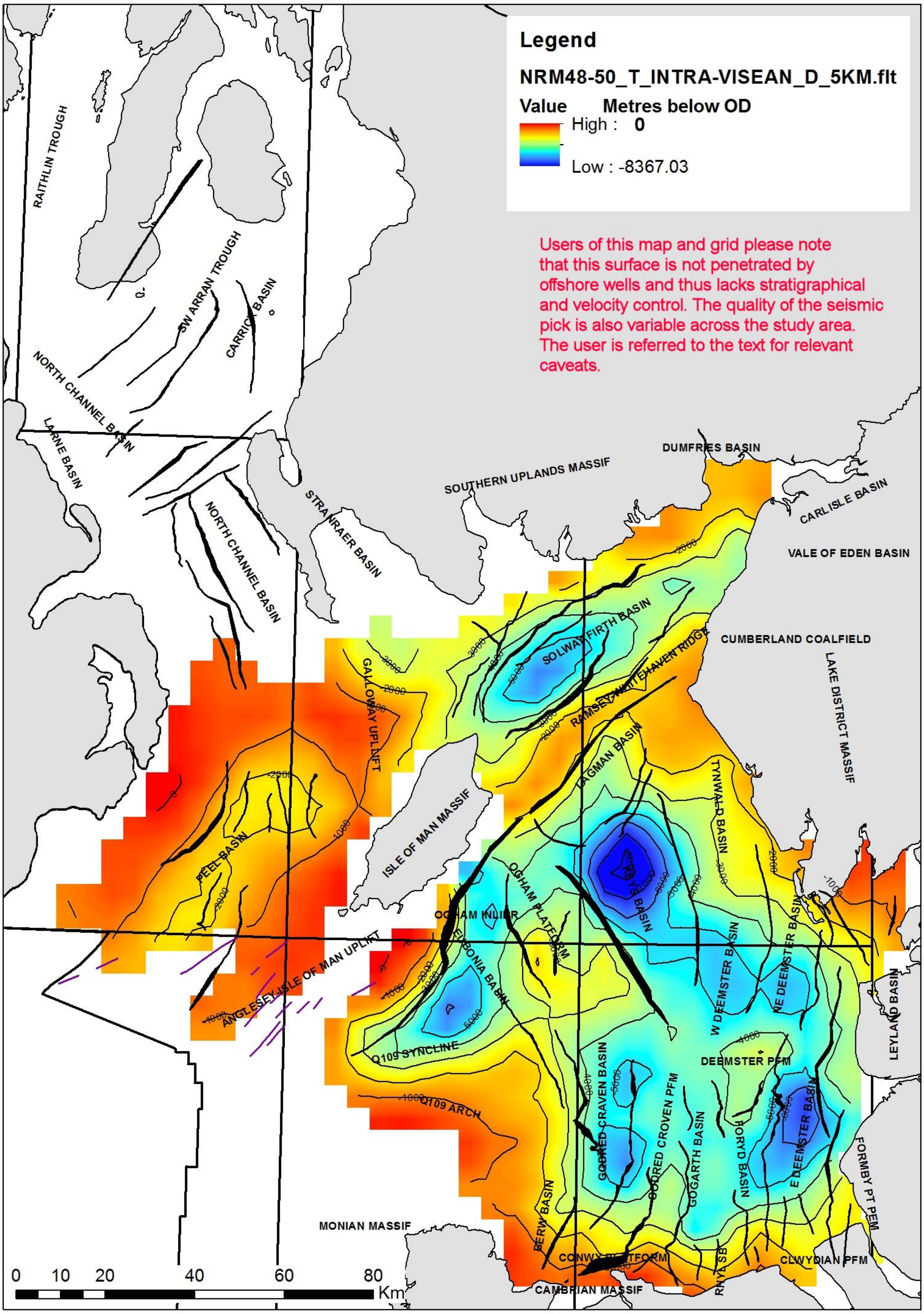


Figure 54 Structure map in depth (metres sub sea level) for the Intra-Visean pick (see text for further details).

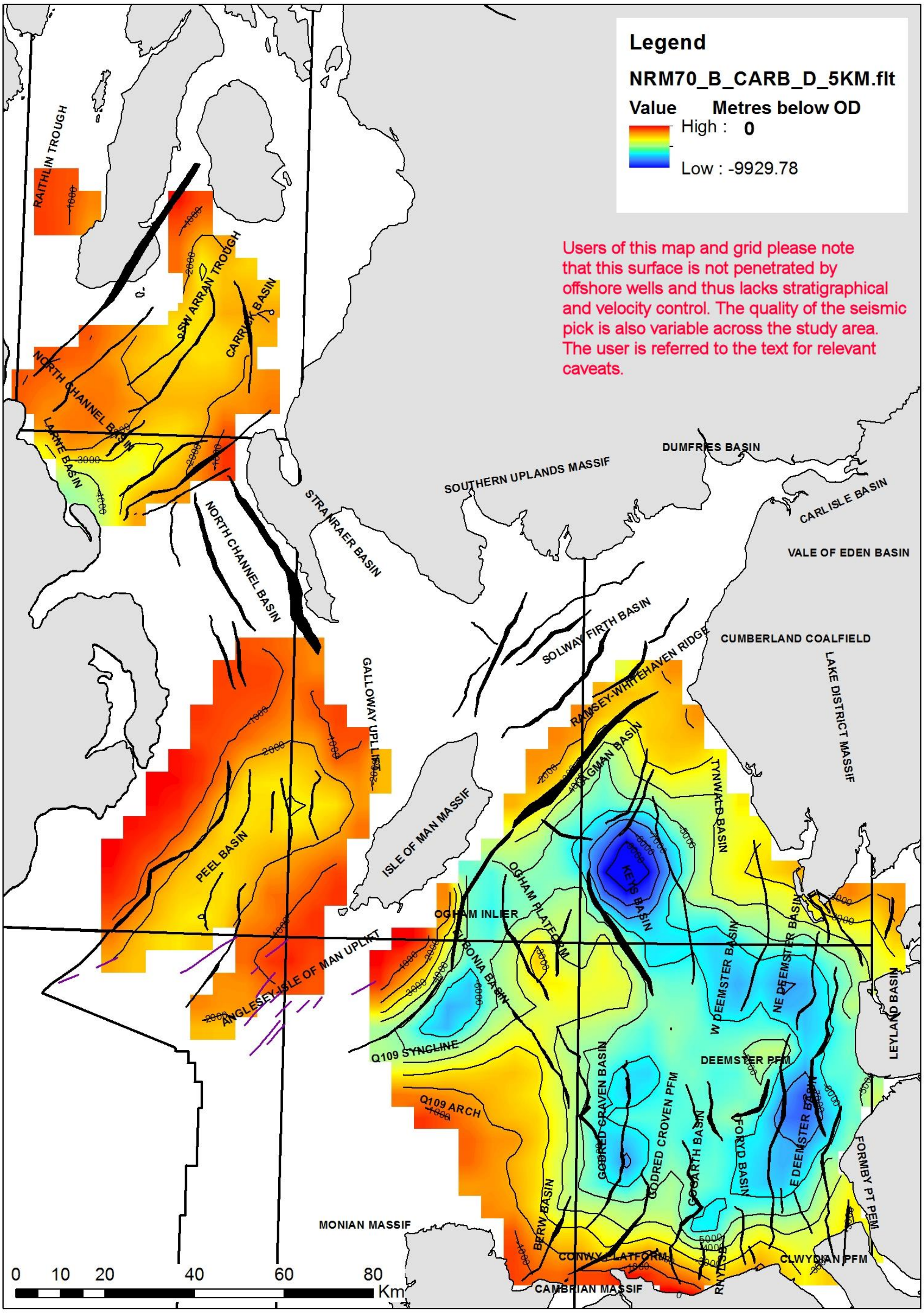


Figure 55 Structure map in depth (metres sub sea level) for the Basal Carboniferous pick (see text for further details).

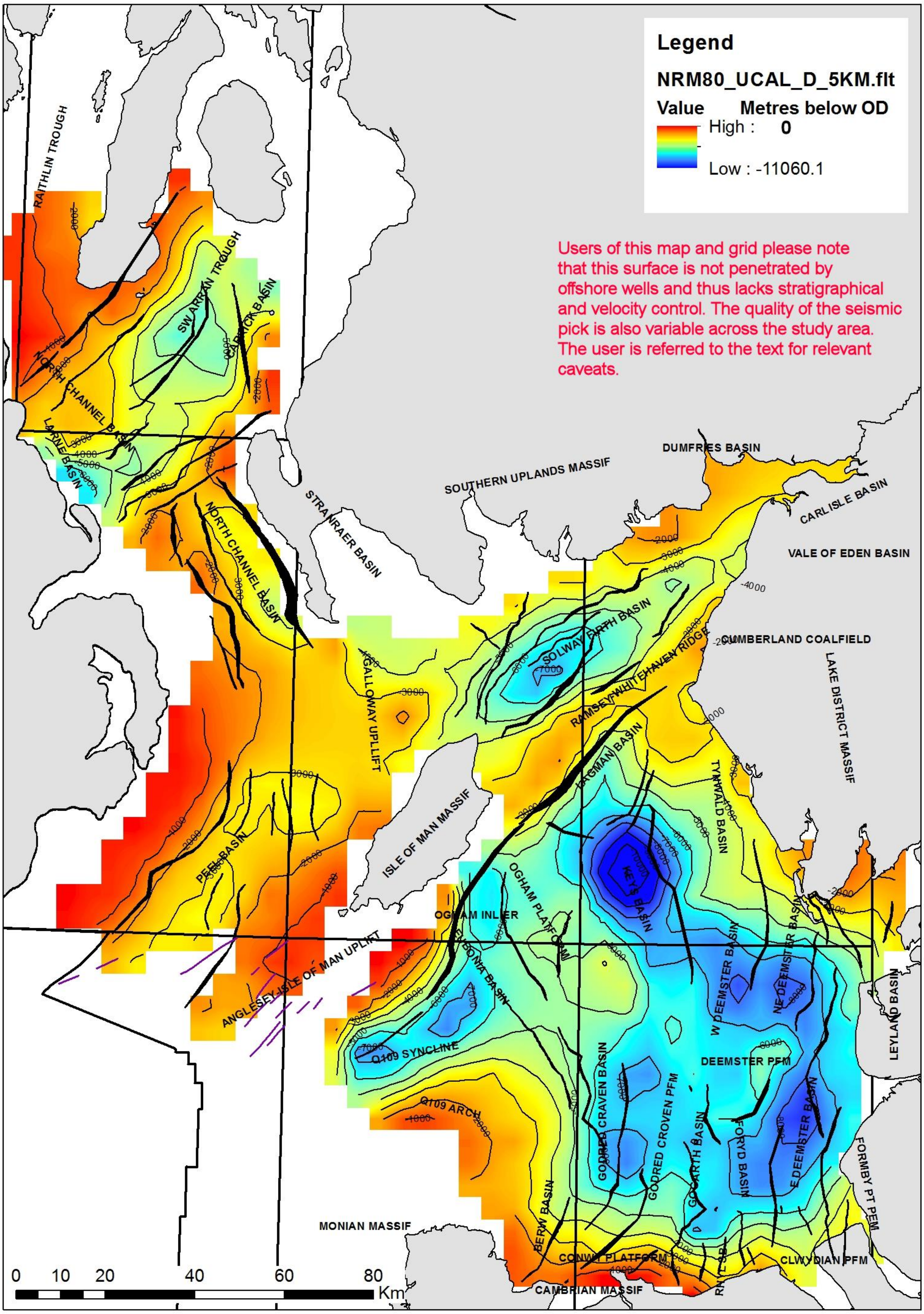


Figure 56 Structure map in depth (metres sub sea level) for the Acadian (Caledonian) Unconformity (see text for further details).

6 Petroleum Systems of the Irish Sea basins

The sections above have described the extent, depths and style of offshore Carboniferous basins in and around the Irish Sea, plus their continuation in Northern Ireland, Scotland, Isle of Man, on the margins of the Lake District, Craven Basin, Lancashire, North Wales and Anglesey. A petroleum system is proven in the East Irish Sea Basin, onshore at Formby and may be present in the Carboniferous of the onshore Rathlin Basin of Northern Ireland (Providence, 2013).

In this section, the petroleum systems of the Carboniferous basins are considered:

1. East Irish Sea Basin, viewed as the western extension to the Pennine Basin onshore
2. Solway Basin (1 well only) overlying the SW extension of the Northumberland Trough
3. Peel Basin (2 wells only) overlying a Carboniferous basin of indeterminate connection
4. North Channel Basin (1 well, Permian-Lower Palaeozoic) overlying a possible but shallow Carboniferous or Devonian basin
5. Larne - South West Arran Trough (no wells offshore but several in Northern Ireland) overlying an extension of the Midland Valley of Scotland.

6.1 EAST IRISH SEA BASIN

In the East Irish Sea Basin (EISB), a proven petroleum system is present, involving a Carboniferous source (Colter and Barr, 1975; Cowan, 1991; Stuart, 1993; Armstrong et al., 1997), the Triassic Ormskirk sandstone reservoir and mudstone and halite seals. The adjacent onshore Carboniferous Pennine Basin is defined by a Late Carboniferous depocentre near Manchester and its inversion to form the Pennine Anticline. Earlier Tournaisian rifts had different trends, NE-SW surrounding the Cheshire Basin (Smith et al., 2005) and NW-SE in the East Midlands (Pharaoh et al., 2011).

6.1.1 History of exploration

The history of exploration begins with the discovery of the Formby Oilfield in 1939, in the West Lancashire Sub-basin (onshore). This field was developed quickly in response to the outbreak of the Second World War. It is a shallow field sourced from the Carboniferous with reservoirs in the Triassic Helsby Sandstone (=Ormskirk Sandstone offshore), overlying Tarporley Siltstone and Quaternary Shirdley Hill Sandstone. It is crossed with numerous N-S trending faults (Falcon and Kent, 1960). After the War extensive drilling attempted to find a Carboniferous field underlying it, without success (Falcon & Kent, 1960).

Offshore the Gas Council (later British Gas) made discoveries after taking over licences where a Gulf/National Coal Board partnership had drilled: The North and South Morecambe fields were large discoveries the recognition of the Bowland Shale as the major source was made by Armstrong et al. (1997).

In 1990, an onshore British Gas well discovered a gasfield at Elswick in Lancashire. The age of the reservoir was given as Permian Brockram equivalent on the well log/reports. An alternative possibility is that the reservoir is of Namurian age (this study). There are no Pennine Coal Measures at outcrop or subcrop (Smith, 1985) near this discovery, highlighting the interpretation that the field is unlikely to have been sourced by Westphalian coals (Smith, 2013).

At about the same time, Hamilton (later BHP) discovered a line of fields parallel with the North Wales coast and at the latitude of Formby in the offshore (Hamilton, Douglas, Lennox). Most of the deep wells of these fields also encountered Millstone Grit below the Variscan Unconformity, as at Formby. Armstrong et al. (1997) studied the geochemistry of the onshore Holywell Shale (Bowland Shale equivalent) and compared the results with oils from Douglas and Lennox fields, which were closely matched. Many additional fields have been discovered subsequently, mostly in the centre of the East Irish Sea basin and mostly containing gas, culminating with the Rhyl discovery in 2009 by Centrica. Only Ormskirk Sandstone reservoirs are utilised as producing reservoirs in the EISB. No significant Carboniferous reservoirs or good shows have been reported and the Permian Appleby Group (Rotliegend equivalent) is also currently unproductive.

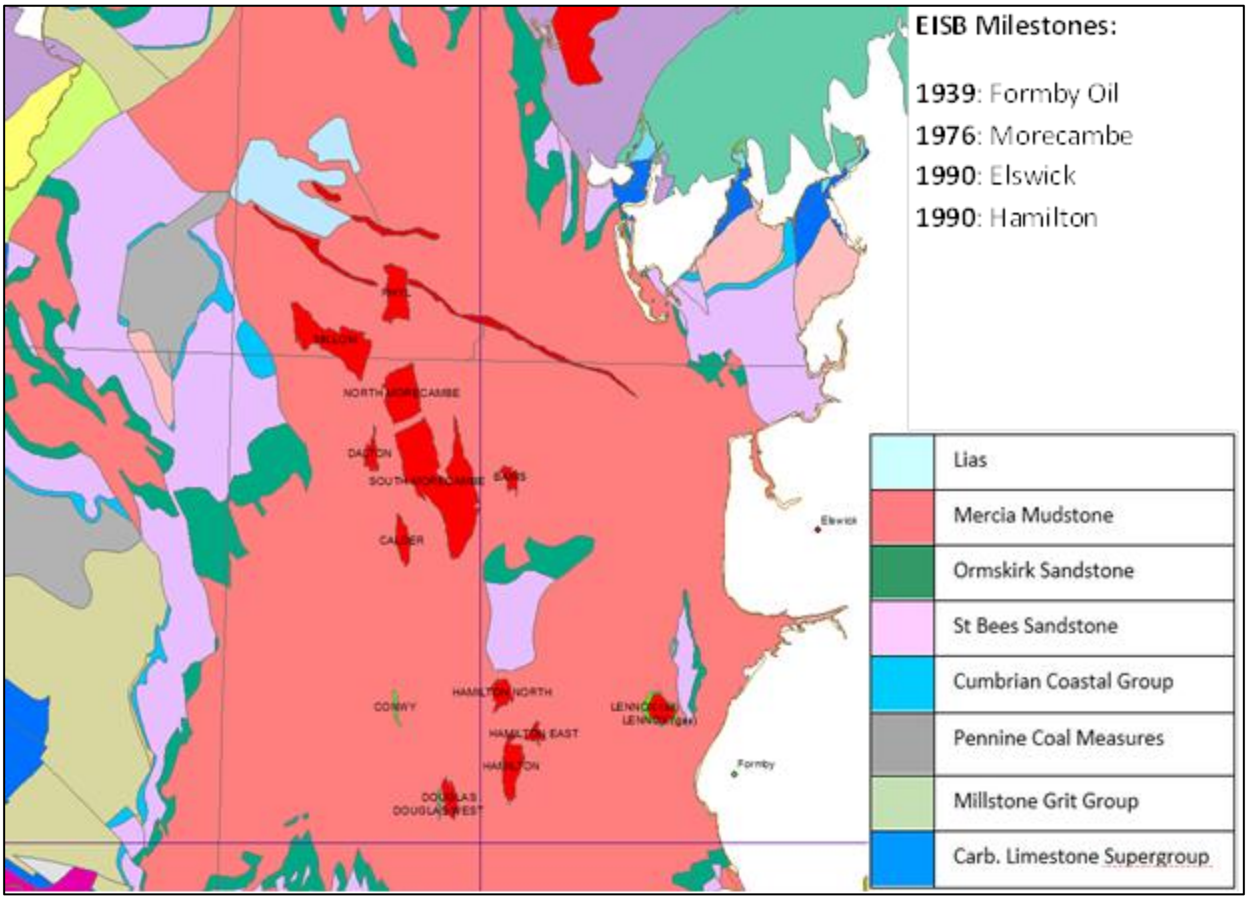


Figure 57 East Irish Sea Basin seabed geology from BGS 1:250,000 offshore DigMap BGS©NERC, fields and milestones

6.1.2 Oil

Oil was discovered in the onshore Formby and offshore Hamilton fields, towards the southern margin of the East Irish Sea Basin in Triassic reservoirs. Conwy is an oilfield in block 110/12 and the Corfe discovery is in block 110/13 to the west. After appraisal drilling, the latter was recorded as uneconomic. Using isotopes the sampled oils (from 110/15- 6, Lennox and 110/13-10, Douglas Oilfield) were correlated with each other, and the Holywell bitumen and the Holywell Shales of north east Wales (Armstrong et al., 1997), thereby proving the Bowland Shale source in this case. These were isotopically lighter (more negative) than Westphalian cannel coals of Type I kerogen, for example those formerly mined and used to make oil at Leeswood. Waxy crude shows in the Millstone Grit in 110/07b- 6 (Zone A, 1510 m-1675 m; Released Geochemical Report) showed an isotopically similar source to shows in 110/07- 2, 110/08- 3 and Formby. The API gravity of the oils range from 40-45 (Hardman et al., 1993) at Lennox and Douglas, to 37 at Formby, perhaps suggesting a less mature source in the onshore field (Armstrong et al., 1997).

6.1.3 Gases

Gases are found in the central part of the East Irish Sea Basin e.g. Morecambe fields. All the gases have similar compositions, comparable with onshore fields and discoveries, except for the proportion of incombustibles (Figure 58, which is based on data from Hardman et al. (1993), Bushell (1986); Yaliz (1997); Haig et al. (1997)). 110/04-1 and 110/04-2 have large gas columns in the Ormskirk Sandstone with an uneconomically large proportion of biogenic nitrogen (Geological Final Well Report 110/04- 2). Carbon dioxide is recorded in increased proportions in the Morecambe and Rhyl fields, which are closest to the Fleetwood Dyke Complex. Hydrogen sulphide appears in the south of the basin in the Hamilton and Calder fields (e.g. 110/7a-4; Blow & Hardman, 1997). It is conceivable that the higher hydrogen sulphide source source derives from a Visean shale sub-basin(s) as hydrogen sulphide springs are known from the onshore Pennine Basin e.g. Kedleston, Aldfield and Harrogate (Smith, 1999). Alternatively, the hydrogen sulphide might derive from reactions in Permian sulphate-rich evaporites.

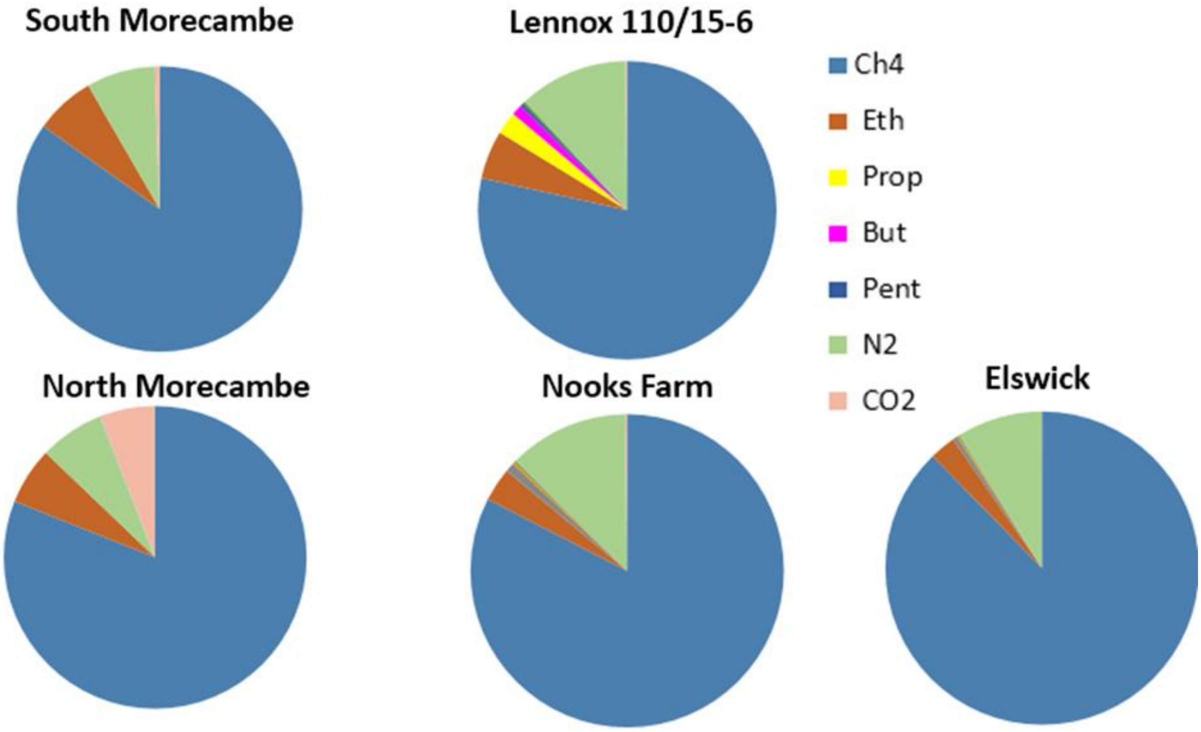


Figure 58 Gas compositions of onshore and offshore fields, after Hardman et al. (1993), Bushell (1986), Yaliz (1997) and Haig et al. (1997)

6.1.3 Stratigraphy of the petroleum system

Carboniferous source rocks are shown in Figure 4 covering the early part of the Namurian and latest part of the Visean where shales are developed. The Carboniferous source rocks are separated from the Triassic Ormskirk Sandstone reservoir rocks by the Millstone Grit Group and, where present, Pennine Coal Measures and Warwickshire Group. Above the Variscan unconformity the Appleby Group, Cumbrian Coast Group and the lower, tight part of the Sherwood Sandstone Group also intervene.

A Pendleian time slice (Figure 59) highlights the the persistence of the relatively deep marine hemi-pelagic successions (Bowland Shale Formation) across the central part of the British Isles, including the Craven Basin, East Irish Sea Basin and extending westward towards the Dublin Basin. The late Pendleian saw the first major influx of thick fluvial and deltaic sandstones into the Craven Basin, both from the north and from the south. The northern basin fill are characterized by a thick pro-deltaic ramp turbidites, overlain by a siltstone-dominated slope succession, in turn overlain by a fluvio-deltaic, delta-top sandstone (Wakefield et al., 2016). The hemipelagic successions have gamma values which suggest potential as source rocks, confirmed by organic geochemistry studies (see 6.16, 6.1.7 below). The overlying successions of the Pennine Coal Measures and Millstone Grit Group have the potential as a source-reservoir unit, with secondary sources from marine influxes and coaliferous sediments.

Clastic intervals within the Carboniferous and Permian successions that are evaluated for reservoir potential include the:

- Appleby Group
- Warwickshire Group
- Pennine Coal Measures Group
- Millstone Grit Group
- Upper Bowland Shale Formation

The Carboniferous Limestone Supergroup has been assessed as a potential reservoir, although the effect of secondary, karstified and fracture porosity has not been analysed. The preservation and thickness of the possible reservoir units is variable, particularly the Carboniferous units beneath the Variscan Unconformity (Figure 4, 17).

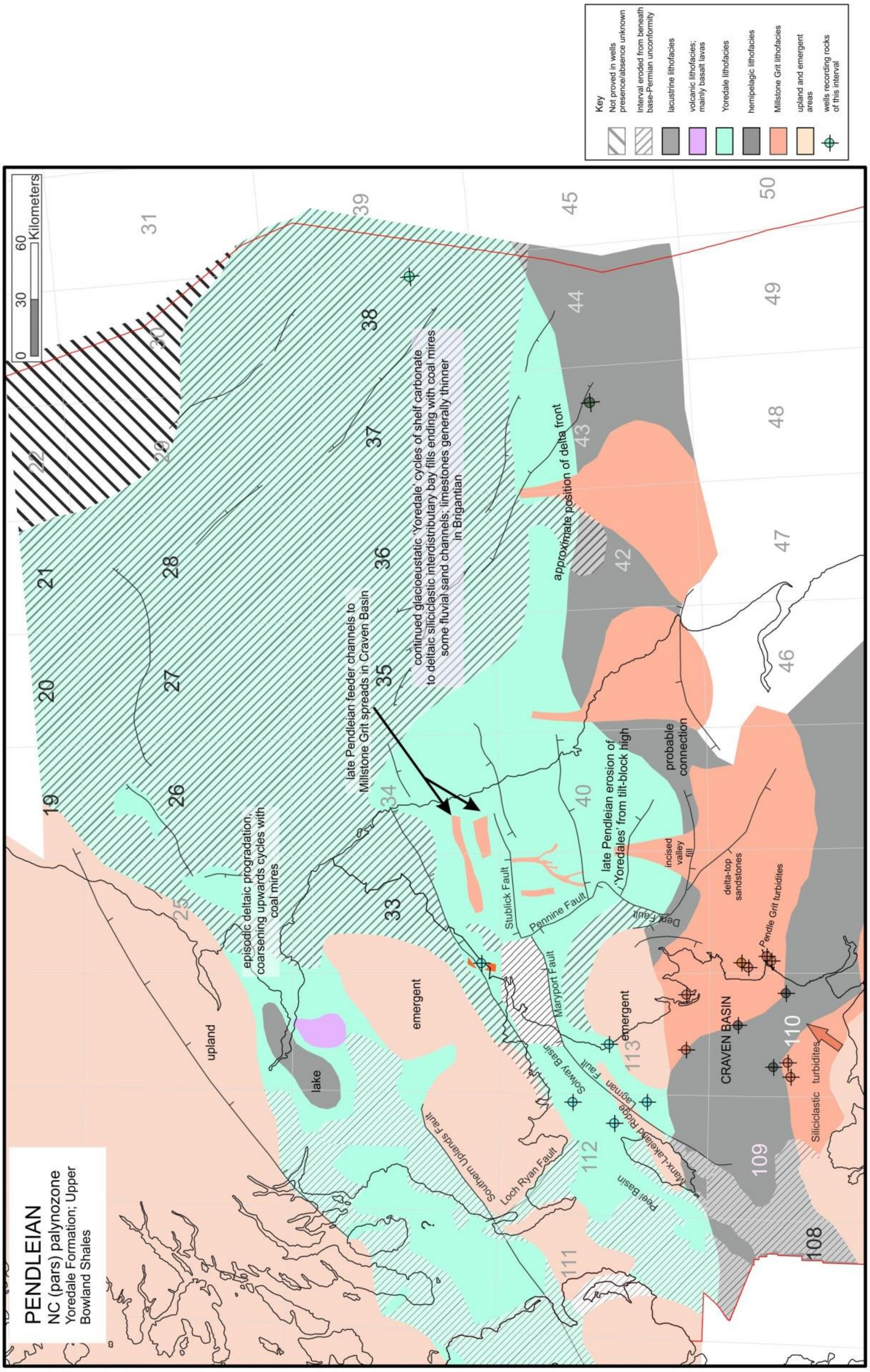


Figure 59 Pendleian palaeogeography showing the Bowland Shale source rock distribution and lateral varation with Millstone Grit facies.

6.1.4 Problems in stratigraphic interpretation

Re-interpretation of well logs and associated core analyses (biostratigraphy, poroperm etc) have provided some alternative stratigraphic interpretations to those shown on the composite log (this study).

Many authors have referred to the problems of secondary reddening of the Carboniferous strata below the Variscan unconformity (Trotter, 1954; Falcon & Kent, 1960; Jackson et al., 1995) in both the adjacent onshore and within the East Irish Sea basin.

In the south of the basin, thick Appleby Group strata overlie the Variscan unconformity and stratigraphic interpretation is straightforward. However, in the Morecambe fields area, the Appleby Group is absent and the Cumbrian Coast Group is interpreted to overlie the Variscan unconformity (Figure 60). This is important because it shows the probable palaeotopography of the Carboniferous surface, deformed and uplifted by the Variscan Orogeny, and the extent of erosion and eventual burial. This area might be analogous to the onshore N-S Pennine Hills and Cleveland Basin Carboniferous successions, where Coal Measures have been removed by post-Variscan erosion (Smith, 1985). The Cumbrian Coast Group comprise a varied sequence of thin sandstones, anhydrites, limestones, halites and mudstones, mostly red in colour. Underlying redbeds could be interpreted either as a mudstone facies of the Appleby or as Warwickshire Group strata. However, the favoured interpretation (this study) combining all the seismic and well evidence is that the red beds in the wells underlying the Cumbian Coast Group directly are secondarily reddened. They often include thin sandstones and high gamma shales and rarely contain coals, and are believed to be mostly of Namurian depositional age.

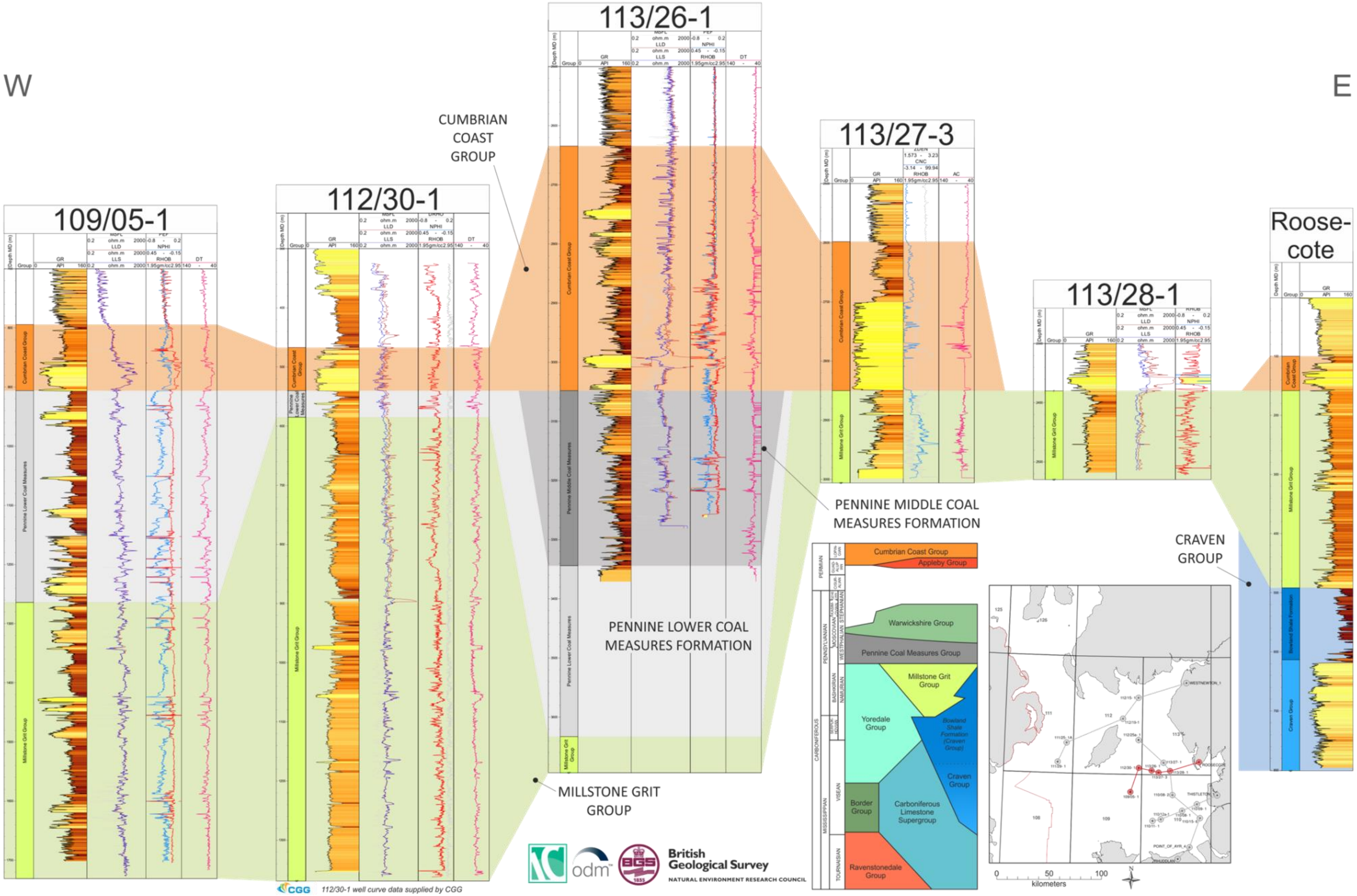


Figure 60 Well transect from 109/5- 1 to Roosecote (onshore north Cumbria).

6.1.5 Conceptual Carboniferous petroleum system models

It seems logical to test the same basin and petroleum model developed from fields in the East Midlands and elsewhere in the adjacent onshore part of the same Pennine Basin, to the Irish Sea offshore (Smith et al., 1995; Smith et al., 2005). In essence, this model envisages migration of hydrocarbons from the Late Carboniferous depocentres to the southern margin of the basin (Figure 61). Onshore, Late Carboniferous reservoirs are most common, with Hardstoft Oilfield anomalous in having a Visean reservoir. Migration to the north is not proved onshore (towards the faulted margins of the Askrigg Block and Lake District). The conceptual model incorporates the relationship of both the East Midlands fields and the Coalport Tar Tunnel mined oilfield to the Pennine Basin hydrocarbon kitchens. By analogy, prospectivity offshore may be possible to the area off the North Wales coast provided southward migration pathways exist.

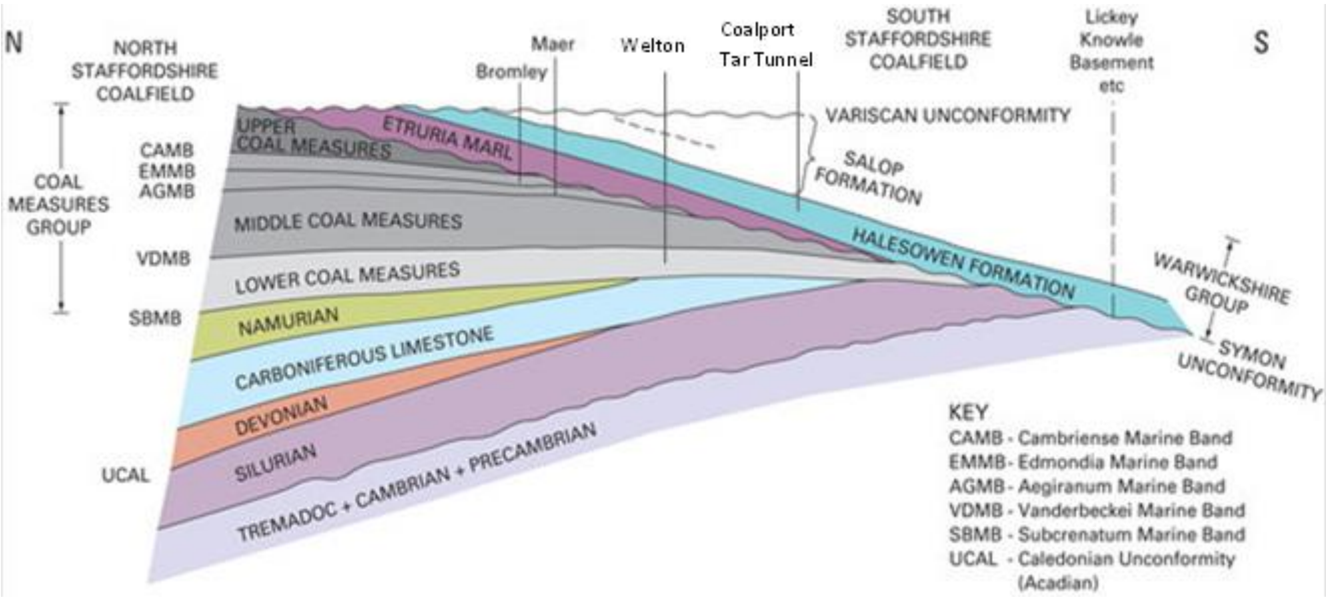


Figure 61 The Carboniferous petroleum model of the Pennine Basin, with selected reservoirs and a source between the Carboniferous Limestone and Namurian, including the intervening Warwickshire Group successor basin (Smith et al., 2005).

In the Cleveland Basin, Permian and Mesozoic faulting has occurred and there are both Carboniferous and Permian aged reservoirs. This area, like the East Irish Sea has been subjected to a double inversion, firstly during the Variscan Orogeny and latterly in Cenozoic times, after Jurassic and Lower Cretaceous subsidence (Kent, 1978). Hydrocarbons have migrated into Permian reservoirs in the Cleveland Basin but are also found in Carboniferous strata (e.g. Kirby Misperton gas field).

Onshore, migration to overlying strata has not occurred in the Cheshire Basin or East Midlands (Smith et al., 1995). Using the East Midlands fields as an analogue for a conceptual Carboniferous petroleum system offshore is problematic due to the small size of the onshore fields.

In the 'Main Graben' of the East Irish Sea Basin, the conceptual model may not be valid because hydrocarbons have clearly migrated to the overlying Triassic strata. The Carboniferous depocentre/generative centre extending towards the Morecambe fields and the Ogham Inlier and towards NW Anglesey was also the probable zone of maximum Carboniferous inversion. However, migration to Carboniferous reservoirs in 'Marginal' areas and in surrounding basins is worthy of testing.

The extent of hydrocarbon migration to the north e.g. Eubonia and Quadrant 109 sub-basins is unclear. There are no onshore fields in the same tectonic position on the faulted northern margin.

6.1.6 Source rocks

One of the key risks in the Palaeozoic of the Irish Sea is the quality, extent and maturity of source rock intervals. Potential source rocks include:

1. Coal Measures and Millstone Grit Group coals (Westphalian and Namurian);
2. Bowland Shale Formation and Millstone Grit Group shales (onshore equivalent Holywell Shale (Pendleian) and Sabden Shales (Arnsbergian)) and older Visean shales (unproven by sample data), for example in the Yoredale Group.

Compilation of the Rock-Eval source rock geochemical data from released legacy reports revealed a small data set, limiting the analysis which could be undertaken (Figure 62; Vane et al, 2016). Where penetrated, the Pennine Lower Coal Measures, Millstone Grit Group and Bowland Shale Formation are mainly gas-prone strata of poor-fair generative potential remaining and mature to the gas window at the sampled intervals in Quadrants 110 and 113 (Figure 62, Vane at al., 2016). Given the maturity levels, source rock potential in these wells is likely to have been depleted by hydrocarbon generation, or the original quality of these source rocks was poor-fair. This could be further examined by detailed review of existing literature (kerogen types, biomarkers) and by new, detailed sampling and analysis. The Cumbrian Coast Group, Appleby Group and Carboniferous Limestone Supergroup sampled in two wells in Quadrant 111 are oil to gas window mature, but have low TOC and low residual hydrocarbon generative potential.

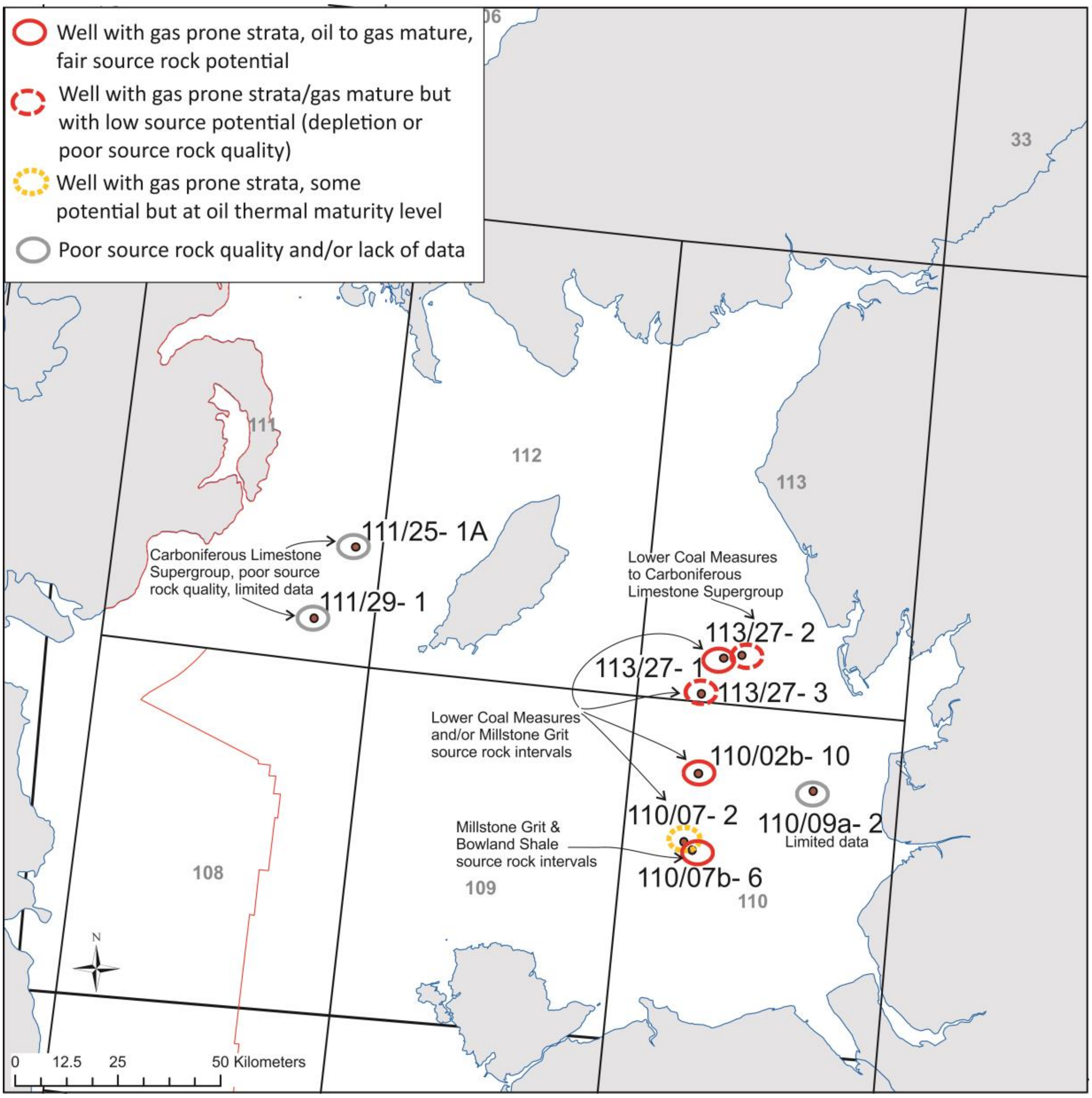


Figure 62 Summary map of well locations and geochemical results for Carboniferous source rocks. From Vane et al. (2016). Note that the wells shown penetrate differing intervals within the Carboniferous.

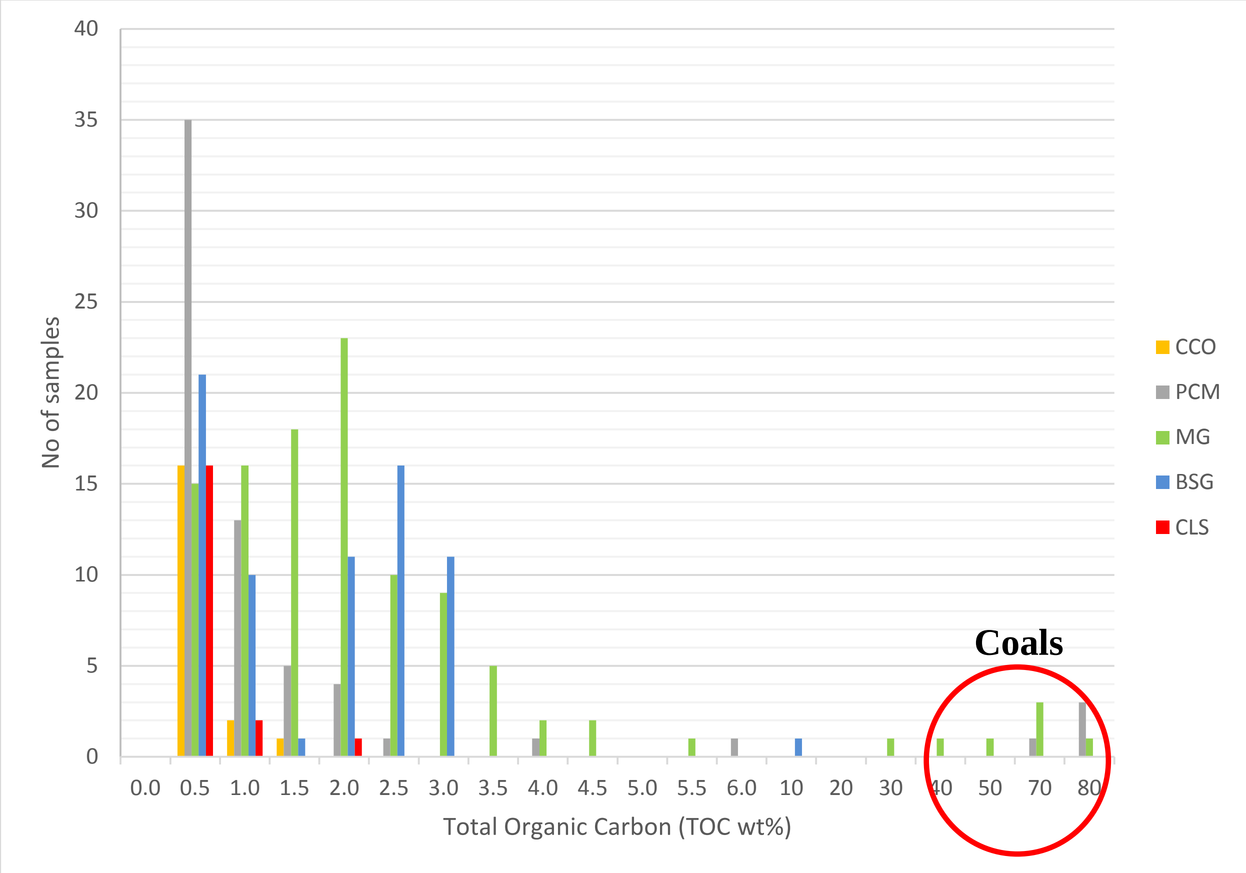


Figure 63 Histogram of weight % measured total organic carbon content (TOC wt%) from legacy data on cutting and core samples in the East Irish Sea Basin. [CCO= Cumbrian Coast Group, PCM= Pennine Coal Measures Group, MG= Millstone Grit Group, BSG= Bowland Shale Formation, CLS= Carboniferous Limestone Supergroup.

264 Carboniferous core and cuttings samples and 20 Permian samples were recorded from the legacy reports (Figure 63). The majority of the Carboniferous samples fall in the 0-3 wt% TOC range with 10% of all values highlighting good organic content (good source rocks in this context have >2 wt% TOC). There are some samples >20 wt% TOC, they are all sampled from the coaliferous Millstone Grit Group (in well 113/27- 1) and the Pennine Coal Measures (in both 110/02b- 10 and 113/27- 1).

The TOC of the Cumbrian Coast Group are expectedly low with all data <2 wt% TOC. Excluding the coaliferous samples (>20 wt% TOC), the Millstone Grit Group has the highest average TOC of 1.62 wt%, followed by the Bowland Shale Formation at 1.56 wt% average. For comparison the onshore equivalent Holywell Shale ranges from 0.7-5%, with an average of 2.1% (Armstrong et al., 1997). Due to limited sample size, the Pennine Coal Measure Group has not been subdivided, excluding the coals it exhibits much poorer TOC with an average of 0.69 wt%.

Data is generally lacking to characterise kerogen types using a Van Kreleven plot, however well 110/02b- 10 (Figure 64) suggest for the Millstone Grit Group and Pennine Coal Measures a kerogen mix between Type II and III. This mixed system can also be expected for the Bowland Shale Formation with a higher proportion of Type II kerogens (though see also Figure 66).

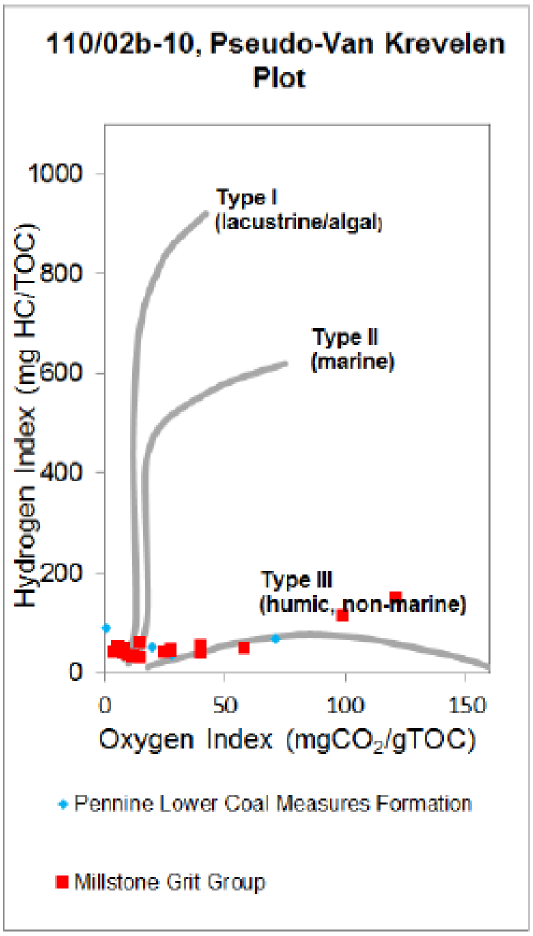


Figure 64 A Pseudo-Van Krevelen plot for Carboniferous strata in well 110/02b- 10

6.1.7 Maturation, generation and basin modelling.

Vitrinite reflectance (VR) data shows an oil and gas window maturity in the wells in which it has been measured (Figures 65, 66). East Irish Sea reservoired oils were considered to have been sourced from 0.75-0.85% maturity and the condensate from > 1.0% (Armstrong et al., 1997). Given the data paucity and complexity for the area of interest, a singular burial trend and maturity profile cannot be defined. For the East Irish Sea study area the burial and thermal history is hard to quantify (Cowan et al., 1999) and especially at the basin margins can change over relatively short distances (tens of kilometres).

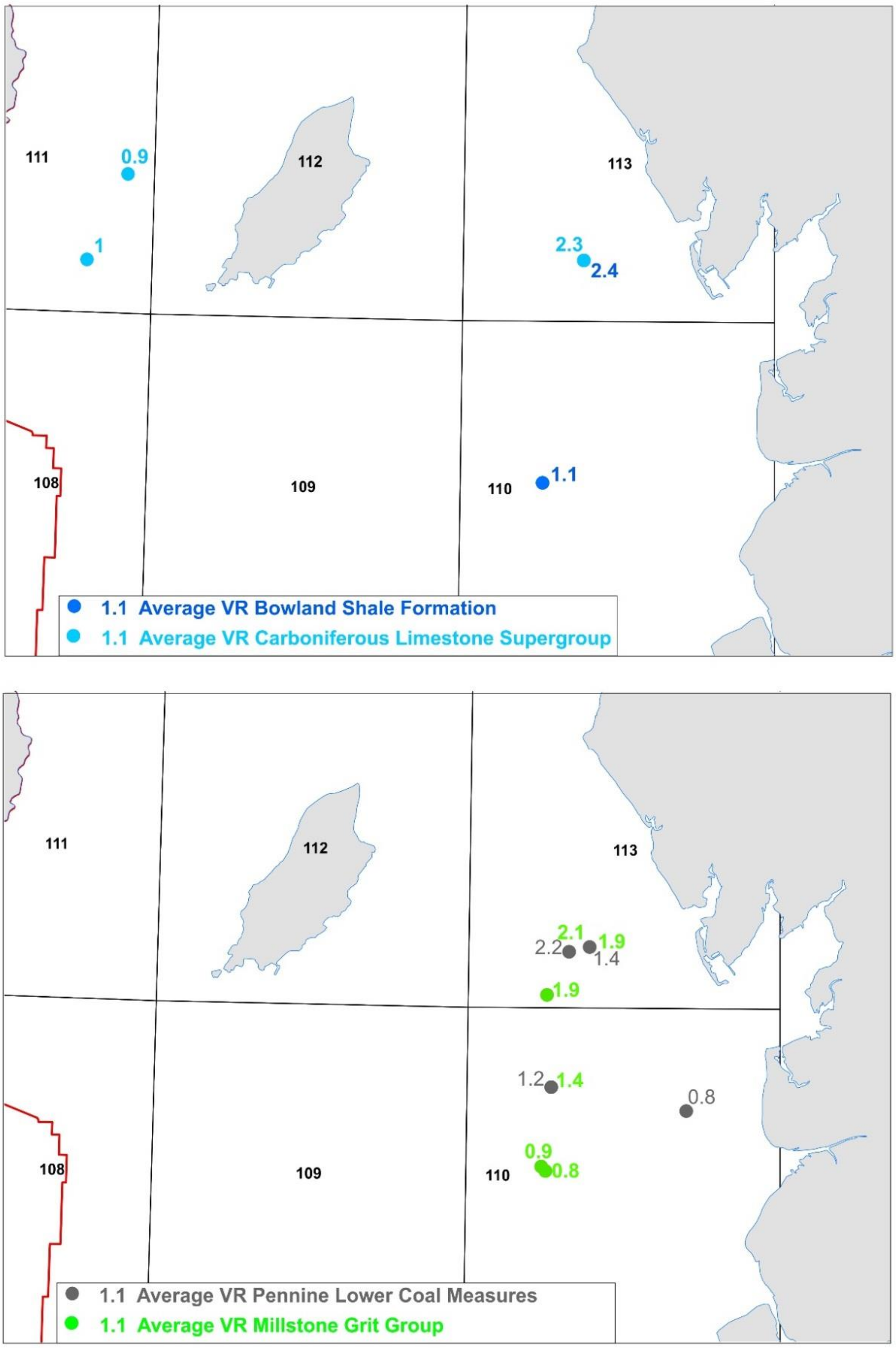


Figure 65 Average maturity values for the specified intervals from measured and calculated vitrinite reflectance data from released legacy reports

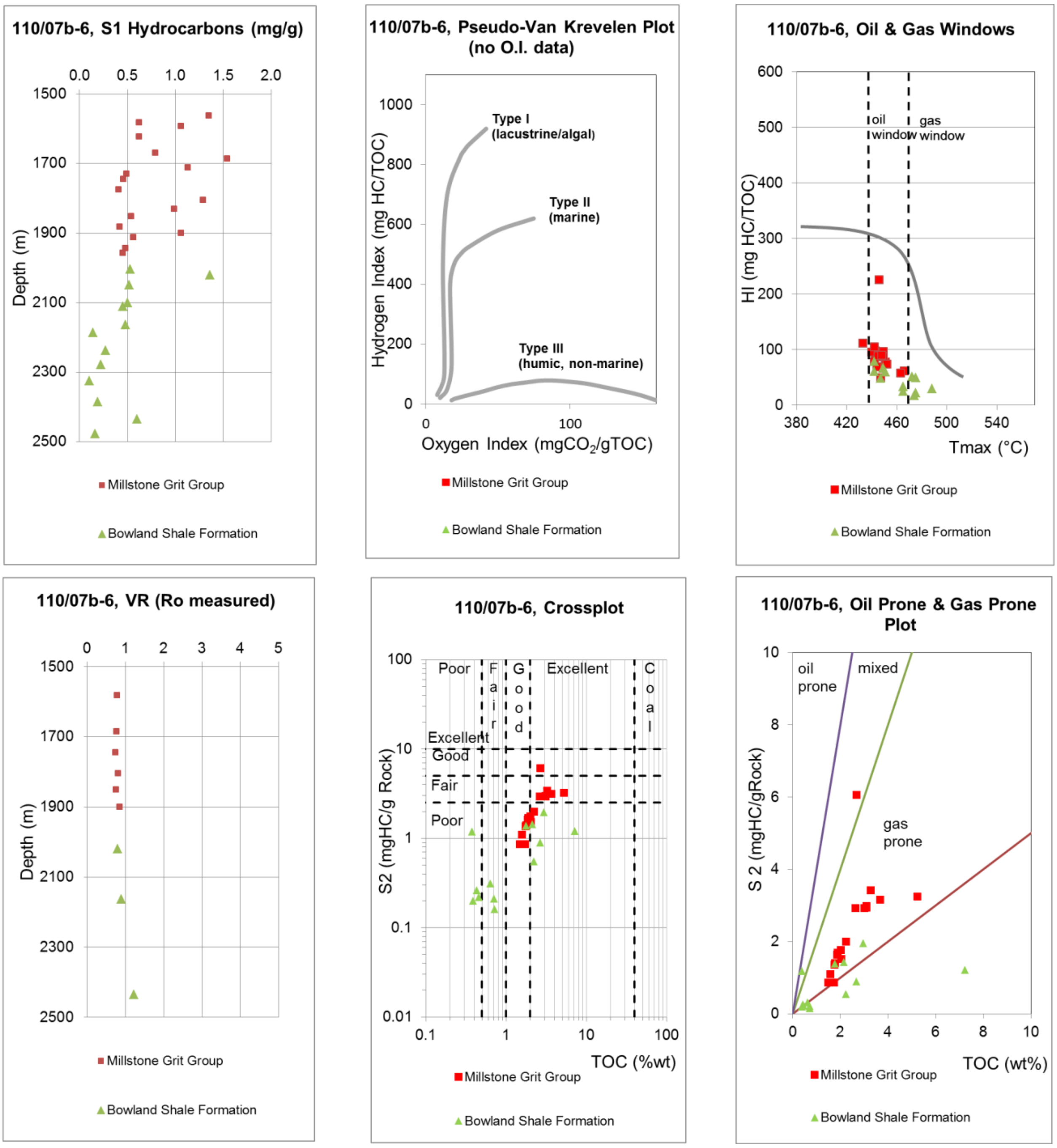


Figure 66: A summary of the available geochemical data for well 110/07b- 6. Data sourced from released legacy reports.

Three wells show a good burial maturity increase with depth within the T_{max} dataset: 110/07b- 6, 110/02b- 10 and perhaps 113/27- 1, indicate progressive oil window into gas window maturity with depth. Some of the T_{max} data indicate a wide spread of temperatures at the same depth, perhaps reflecting reworked and caved material in addition to in situ measurements (Figure 67). Onshore Isle of Man boreholes (Shellag, Ballavarkish, Black Marble Quarry) show a similar range of T_{max}, albeit with few samples (Racey, 1999).

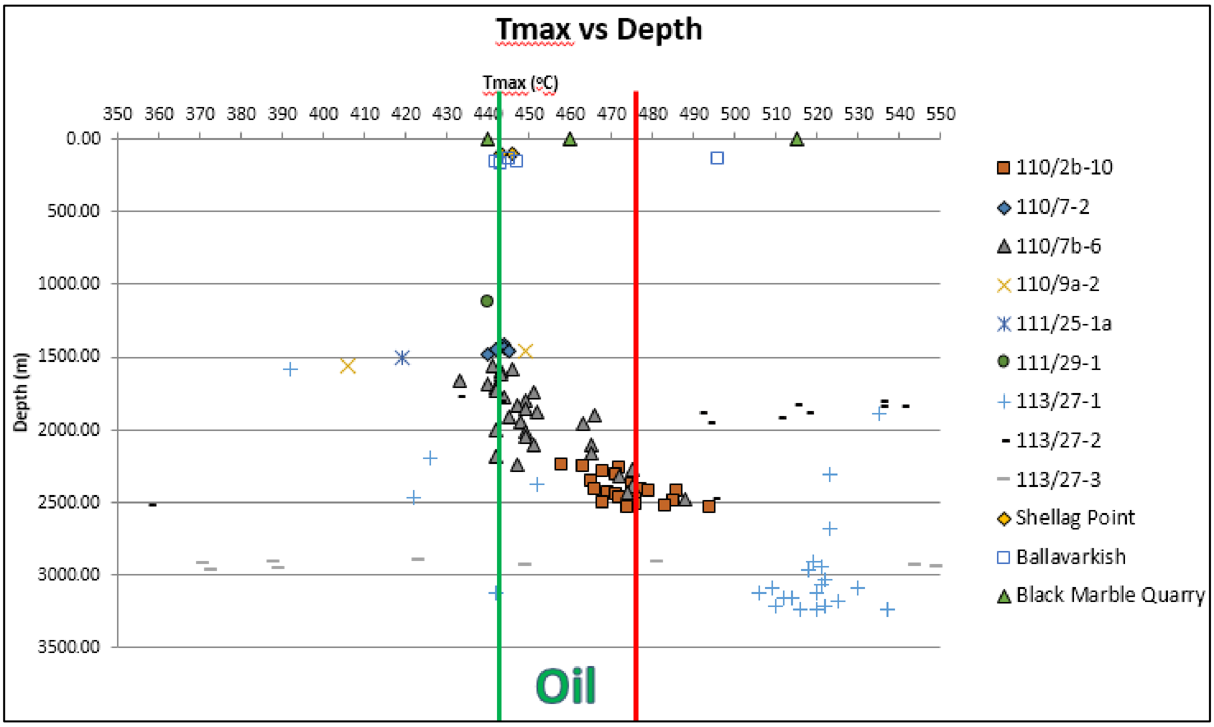


Figure 67 T_{max} versus depth, showing the oil window and the spread of different measurements at the similar depths in some wells.

Basin modelling

A lack of post Jurassic strata has meant that the modelling burial and thermal history of the East Irish Sea Basin has entertained geologists for the past 30 years, with many studies (Cowan et al., 1999; Quirk et al., 1999 and references therein), often with quite different burial histories, for example Cenozoic uplift estimates ranging from <1km to up to 3km.

Apatite fission track analysis (ATFA) can be used to determine the thermal history of a rock however there are temperature limitations which means above 125°C the thermal indicator is completely reset (Giles and Indrelid, 1998), in the East Irish Sea this usually means the AFTA only records the Cenozoic to recent history (Green et al., 1997). There have been many studies to try to constrain the complex basin history of the Irish Sea area, especially the significant amount of Cenozoic uplift and volcanism, and changes in paleo-heat flow associated with those events.

In new work for this study, well 110/07b- 6 was chosen for burial and thermal modelling as it had the most complete geochemical profile (Figure 66) and thick Carboniferous section (Gent, 2016). The well is situated on a minor Variscan high structural position, and is considered reasonably representative of the more marginal areas of the basin. The burial model was matched to the measured VR profile and the calculated VR profile (from T_{max}) (Figure 68), it includes a 700m uplift event in the Late Carboniferous, followed by a minor 150m uplift in the Cimmerian, and a final 1100m uplift and increase in palaeo-heatflow in the Cenozoic. Burial of the Bowland Shale Formation source rock in the Carboniferous reached the early-mid mature oil window before uplift and deeper burial in the Early Cenozoic, just reaching main gas generation in the base of the drilled strata, consistent with the shows in the well geochemical report (Figure 69).

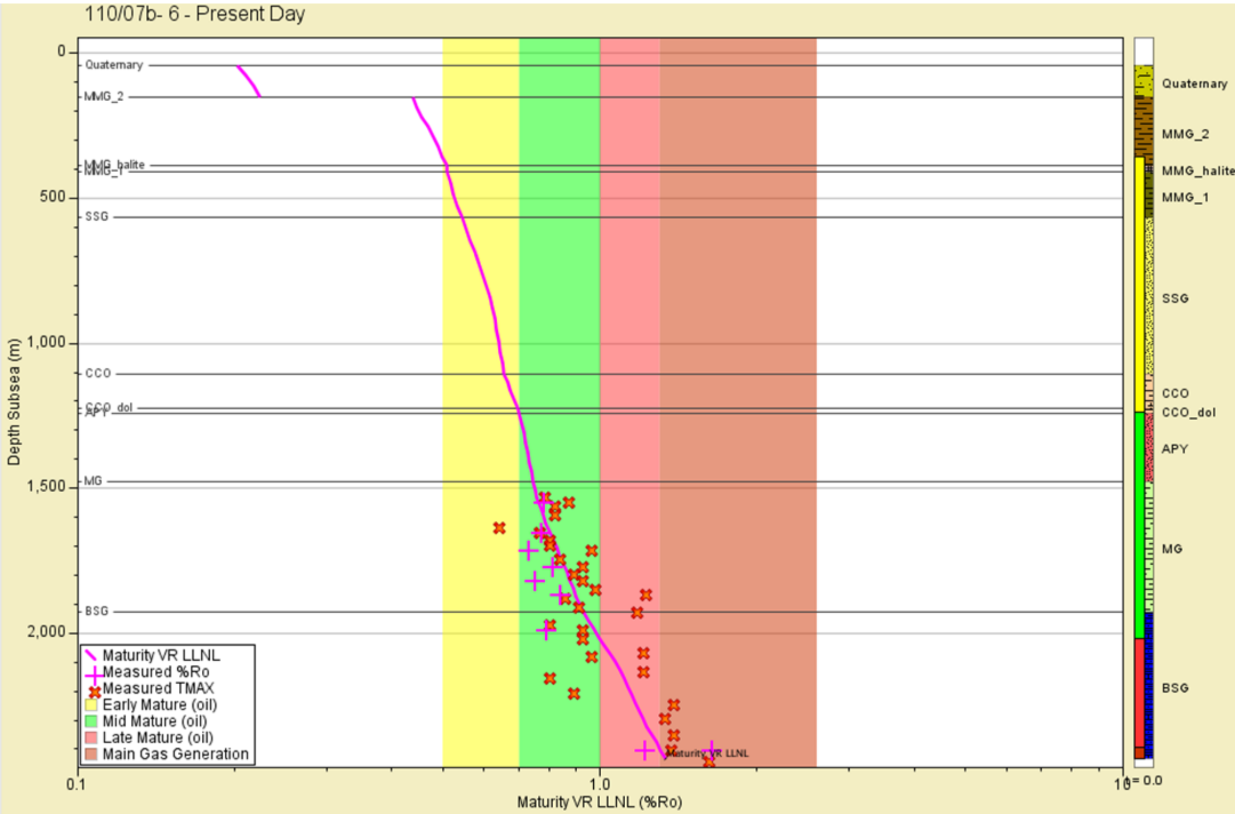


Figure 68 Depth plot showing model results, maturity data and maturity windows for 110/07b- 6

Further geochemical sampling of Carboniferous sedimentary rocks could provide a very useful tool in unravelling the burial history of the East Irish Sea Basin and surrounding areas.

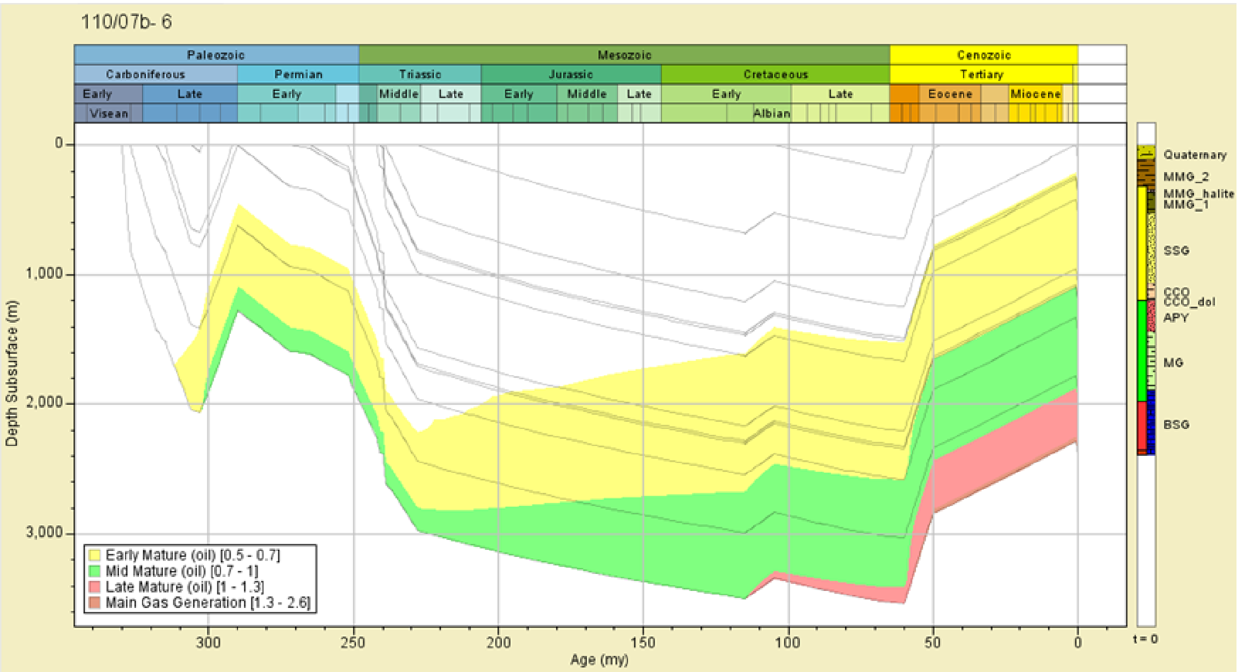


Figure 69: Modelled burial history for 110/07b- 6 showing the Bowland Shale source rock entered the main gas generation window in the late Cretaceous-early Cenozoic. The well terminates in the Bowland Shale Formation, the base of which is not reached

Carboniferous trap formation, generation and migration were all likely to have occurred before the Variscan Orogeny. However, subsequent uplift would have almost certainly breached the traps. Migration and trap formation was renewed in the Mesozoic and Cenozoic times, with any modern day hydrocarbon accumulations having survived the potential structural breach as a result of the Cenozoic uplift event (see Section 4 and 5).

6.1.8 Migration

Migration to Triassic reservoirs and traps has clearly been successful as evidenced by the producing oil and gas fields of the East Irish Sea basin. Oil migration to the Triassic Hamilton fields may have occurred vertically along faults in Jurassic and Cretaceous times (Yaliz, 1998; Haig et al., 1998). As the basin depocentre widened and new areas came into the oil window additional hydrocarbons may have been generated and continued to migrate southward. The basin depocentre entered the gas window and gas migrated into the Morecambe and other fields. This may have occurred both pre- and post- Late Cimmerian uplift/sea-level fall (Bushell, 1986).

In the conceptual Carboniferous petroleum system model (section 6.1.5), migration is away from the steadily deepening and expanding hydrocarbon kitchen towards the margins of the basin, where these strata fail by thinning and overlap (Figure 61). In the north the boundary is probably faulted (Lagman, Eubonia and Lake District faults). Uplift of the basin centre in pre-Warwickshire Group times and during the Variscan Orogeny probably did not affect this direction of migration, assuming that ‘St George’s Land’ to the south was also uplifted. Some hydrocarbons may be retained in the source, as a potential tight shale play as seen onshore Lancashire.

6.1.9 Potential reservoirs

A reservoir evaluation has been undertaken for both Permian and Carboniferous intervals, based on limited measured porosity and permeability data and continuous petrographical interpretations for 8 wells (Hannis, 2016). The aim of the reservoir evaluation was as a quick look regional overview. Net to gross, porosity and basic permeability estimates were calculated for each formation, Table 1 shows a summary of the petrophysical calculations and measured porosity and permeabilities for the formations encountered in the selected wells. Generic cut-offs have been applied to give a broad indication of the Net where:

- Clay volume is less than 50%.
- Effective porosity is more than 5%.
- No coal or salt intervals are identified.

In general, the results illustrate reasonable porosities (5-19 %) and mainly poor permeabilities (0.1-10 mD). Further permeability studies and distribution studies of the Millstone Grit sandstone intervals could be worthwhile (Figure 70).

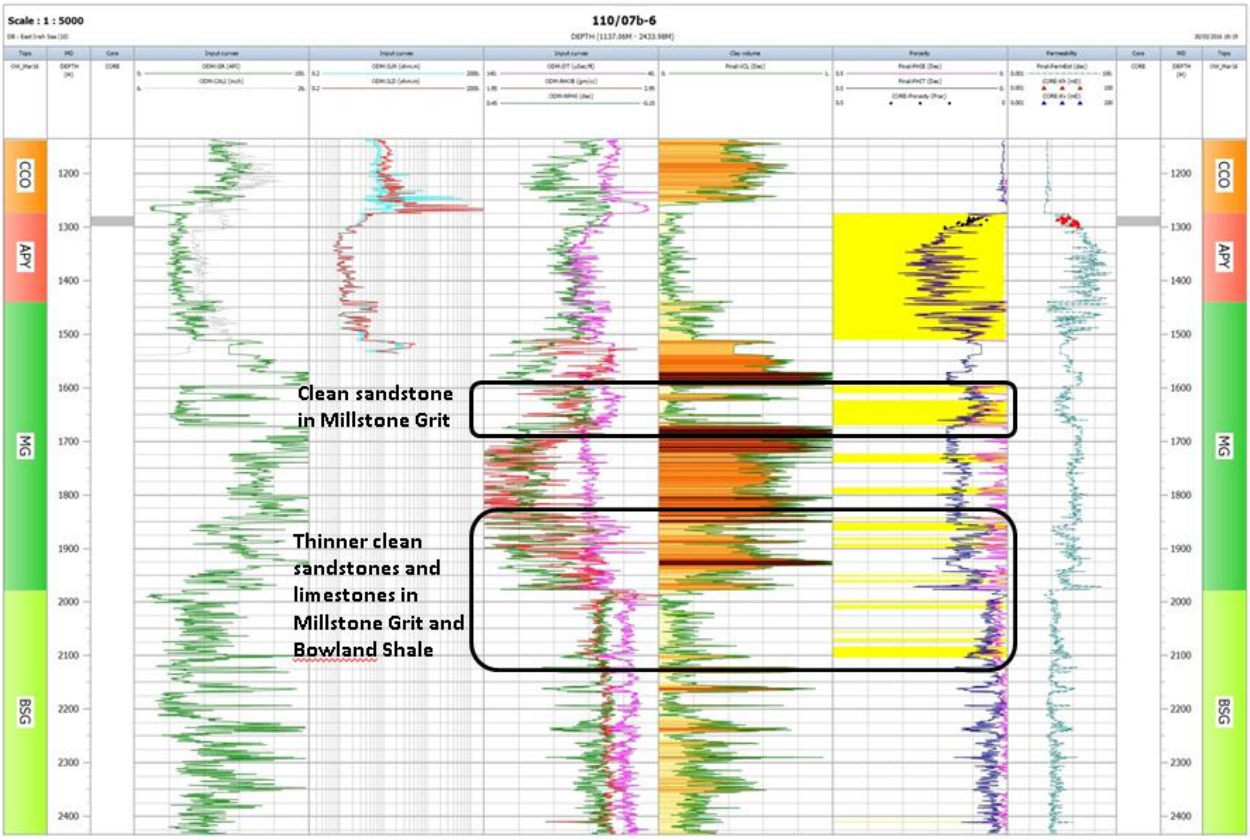


Figure 70 Petrophysical interpretation of well 110/07b- 6 highlighting porous sandstone intervals in the Millstone Grit Group and the Bowland Shale Formation. CCO= Cumbrian Coast Group, APY= Appleby Group, MG= Millstone Grit Group, BSG= Bowland Shale Formation (from Hannis, 2016)

Stratigraphic unit name	Top	N/G	Log curve derived (for net intervals): Highest Av PHIE	Log curve derived (for net intervals): Highest Av PermEst	Core measured (for parts of the units): Highest Av PHI	Core measured (for parts of the units): Highest Av Perm (Kh)	Core measured (for parts of the units): Highest Av Perm (Kv)	Comments
Cumbrian Coast Group	CCO	0.07	0.14	0.17	0.04	3.06		
Appleby Group	APY	0.72	0.19	6.89	0.13	0.80	7.90	Highest net to gross, highest porosity. Highest permeabilities values in the 50-100 mD range for several wells (see Tables 1 & 2).
Pennine Coal Measures Group	PCM	0.08	0.11	0.79	0.02		0.01	
Pennine Middle Coal Measures	PMCM				0.04	0.06		
Pennine Lower Coal Measures	PLCM	0.09	0.11	0.20	0.06	1.07	0.00	Low NTG (although third highest of the units examined). Reasonable average porosity. Permeabilities appear low. Highest values of 175 mD in 1 well, but with no core data over the PLCM interval in that well (see Table 1).
Millstone Grit Group	MG	0.10	0.11	367.74	0.06	0.04	0.05	Low NTG, but highest permeability (low confidence: high permeabilities seen in log estimates in only 1 well, 113/27-2, with relatively poor core-log data fit)
Bowland Shale Formation	BSG	0.03	0.07	0.75				
Yoredale Group	YORE	0.02	0.07		0.01	0.00	0.00	
Great Scar Limestone Group	GSCL	0.00						Matrix porosities less than 5% therefore not considered to have any 'net' using the cut offs applied
Carboniferous Limestone Supergroup	CL	0.00	0.05					Matrix porosities less than 5% therefore not considered to have any 'net' using the cut offs applied

Table 1 Synthesis of petrophysical results by formation (from Hannis, this study). NTG = Net reservoir thickness to gross formation thickness. Permeability figures are in mD, porosity in percent.

In the core measures dataset, a general porosity versus permeability correlation is exhibited (Figure 71). Future work could investigate the location of the wells to see how the porosity versus permeability trend changes depending on the geographical location, facies and burial depth.

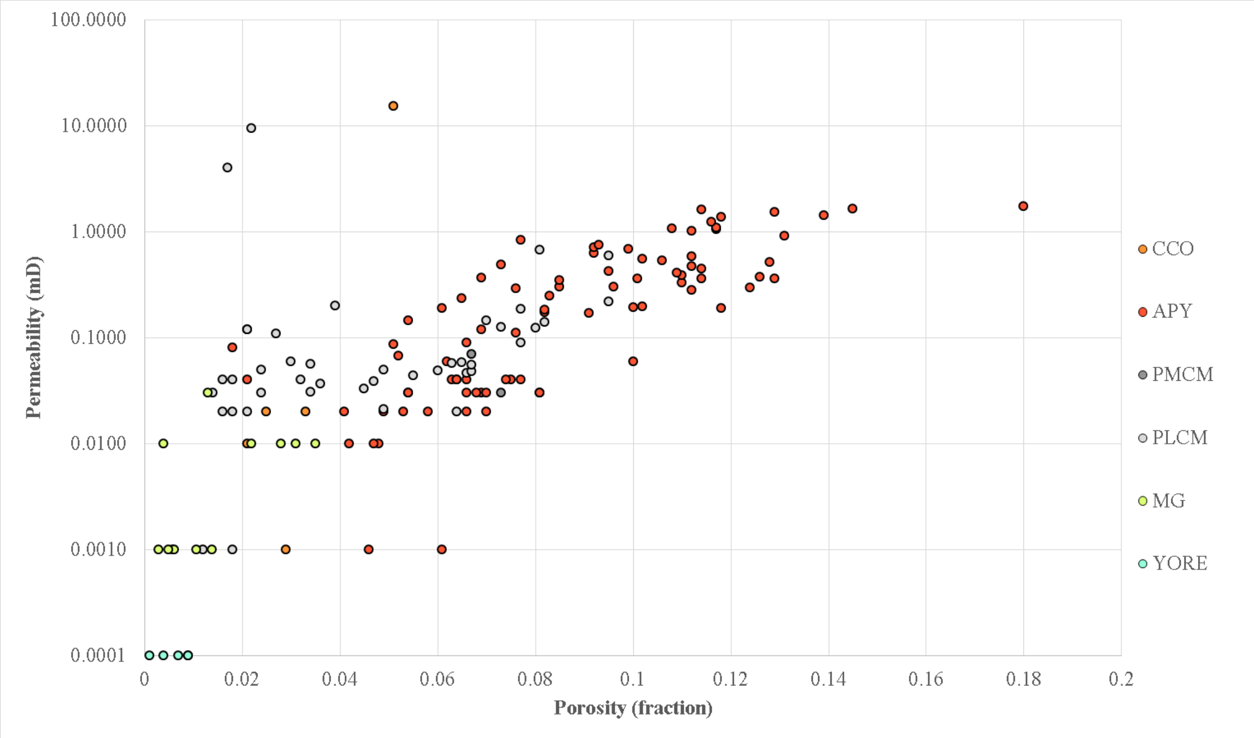


Figure 71 Cross plot of core porosity and permeability for East Irish Sea Basin samples. APY = Appleby Group, CCO = Cumbrian Coast Group, PMCM Middle Coal Measures, PLCM = Lower Coal Measures, MG Millstone Grit, YORE = Yoredale Group

Pharaoh et al. (2016a) compare seismic velocity trends from check shot data in the Namurian and Westphalian succession, with similarities in marginal areas to the Triassic Ormskirk Sandstone reservoir. Though further petrophysical and petrological studies are required, the relationship between Carboniferous and Triassic velocities gives encouragement that Carboniferous reservoir quality at the margins of the East Irish Sea basin may be improved compared to the basin centre.

6.1.9.1 Appleby Group

The Permian, aeolian-dominated deposit of the Appleby Group (including the Collyhurst Sandstone) is a prospective reservoir interval. The arrangement is commonly defined by a basal breccia, overlain by a thick clean sequence of aeolian sandstones, culminating in an upper sequence of breccias (Wakefield et al., 2016). Maximum measured core porosity is 21% with a formation average in all wells of 11%. Permeability however is poor, with maximum measured permeability of 71.5 mD (vertical (Kv)), and a formation average of 0.37 mD (horizontally, Kh) and 7.90 mD (vertically).

Petrophysical analysis has confirmed the group as being a sandstone dominated interval with an average net to gross of 0.72. Porosity and permeability calculations match with the core measured values, with the highest average porosity calculated at 19% and highest average permeability estimates of 6.89 mD, with some estimates in the 50-100 mD range for several wells (Hannis, 2016).

6.1.9.2 Warwickshire Group.

The Warwickshire Group is the equivalent of the Ketch Formation of Quadrants 43, 44, 52 in the Southern North Sea.

The onshore Warwickshire Group of North Wales and Cheshire Basin comprises predominantly red, brown, purple-grey and locally green-grey siltstones and mudstones. However, potential reservoir sandstones can be locally significant. The amount of sandstone to mudstone and siltstones within constituent formations of the Warwickshire Group varies considerably.

In west Cumbria, a distinct component of the Warwickshire Group is recognised. The Whitehaven Sandstone Formation, at least 280 m thick (Akhurst et al., 1997; Dean et al., 2011) is mainly a red to deep purple or purplish brown, cross-bedded, micaceous, medium- to coarse-grained sandstone (Wakefield et al., 2016; Figure 73).

The Halesowen Formation (Warwickshire Group) reservoir was productive in a small mined Tar Tunnel field in Shropshire during the 18th and early 19th century. In the East Midlands, the Warwickshire Group has better reservoir characteristics than productive older Late Carboniferous strata but is spatially confined to the synclines (BGS, 1983). Investigation of the Warwickshire Group as a reservoir interval is worthwhile, though its extent is interpreted to be limited in the East Irish Sea Basin (Figure 17).

There are no well penetrations and therefore no reservoir data for the Warwickshire Group within the East Irish Sea Basin. Data from Quadrant 53 and the English Midlands shows that an average porosity of 16% is likely, with a permeability of several hundred mD, although the bulk of the data was from above 600 m depth (Figure 72). Porosity and permeability are likely to decrease with depth.

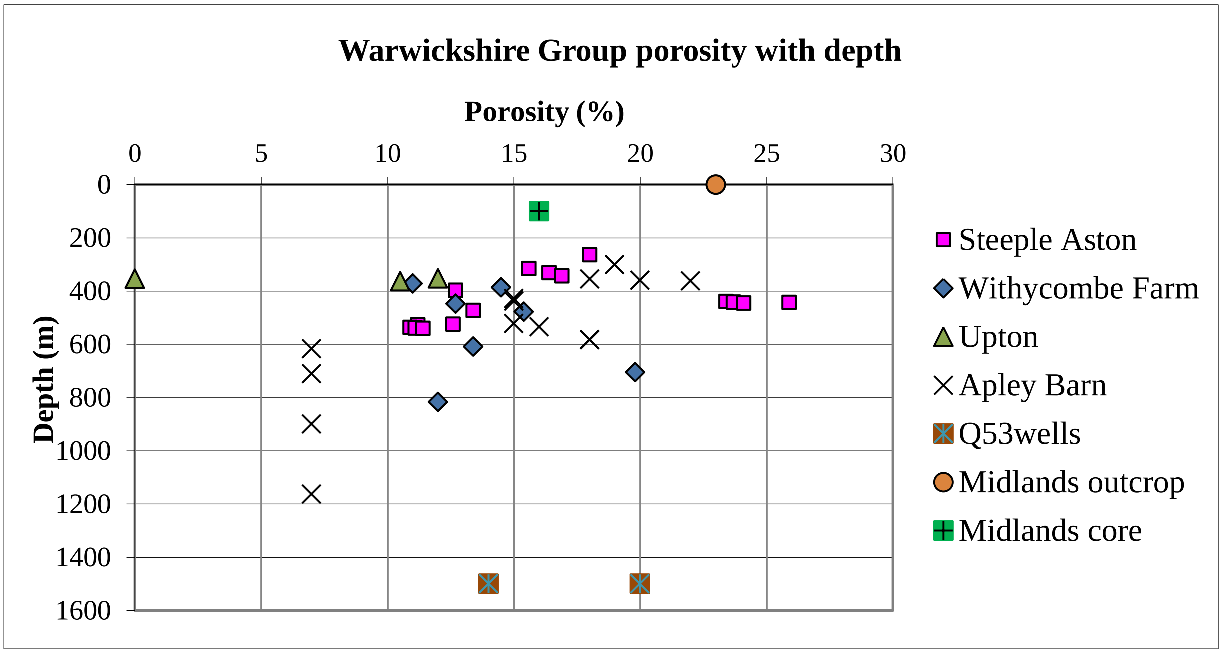


Figure 72 Porosity of Warwickshire Group onshore and in Quadrant 53

Figure 73 Irregular bedding in Whitehaven Sandstone of the Cumbrian coast BGS photo P202266 BGS©NERC. All Rights Reserved 2016

6.1.9.3 Pennine Coal Measures Group

The Pennine Coal Measures comprises interbedded grey mudstone, siltstone and pale grey sandstone, commonly with mudstones containing marine fossils in the lower part of the middle and lower subdivision, and more numerous and thicker coal seams in the upper part. The group shows an overall blocky to erratic log response, with thick high gamma mudstone and siltstone intervals and relatively thin (3-15m) low gamma sandstones. The sandstones show considerable variation in wireline log character, including 'box-car' motifs in thick, distributary channel sandstones (Wakefield et al., 2016).

Onshore, the Coal Measures sandstones are frequently encountered, (e.g. Cefn Rock and Hollin Rock of NE Wales coalfields, Worsley Delf Rock, Prestwich Rock and Newton Rock of Lancashire Coalfield) and are approximate equivalents to the productive sandstones in basinward East Midlands fields (e.g. Oak Rock, Crawshaw Sandstone, Wingfield Flags).

Maximum measured core porosity is 9.5%. Permeability is generally poor with a maximum measured permeability of 9.43 mD (Kh), and a maximum calculated formation average for Kh of 0.42 mD. However permeability has been estimated to reach up to 175 mD in well 110/02b-9 (Hannis, 2016).

There may be a Westphalian sandstone, present in the subsurface offshore north of the Rhuddlan well (Figure 74) but the limited extent of the Coal Measures (Figure 17) and lateral variability will limit reservoir continuity.

6.1.9.4 Millstone Grit

The Pendleian to Yeadonian aged Millstone Grit Group comprises cyclic successions of quartz-feldspathic sandstone, grey mudstone, thin coal and prominent seatearths, resulting from deposition by repeated progradational deltas. Common marine bands are present and represent discrete flooding events. Thick reservoir intervals are uncommon, with initial turbidite lobes passing into delta top deposits with thin sandstones typically contained within sheetfloods, overbank deposits and stacked channels. Onshore, and potentially offshore, thicker sandbodies (up to 50 m) occupy incised valleys (Wakefield et al., 2016).

Maximum measured core porosity is 10% with a formation average in all wells of 6%. Permeability is poor with a maximum measured permeability of 15.2 mD (Kh), and a formation average for Kh and Kv of 0.04 mD and 0.05 mD respectively.

Petrophysical analysis provides a more promising outlook for the group, although the average net to gross is 0.01. When sandstones are encountered they have been calculated to have a good porosity with the highest average porosity of 11%. Calculated permeability continues to be poor with an average estimated to be 0.6-2.1 mD, however estimates from well 113/27-2 show an average of 367.7 mD suggesting that more analysis of these sandstones would be beneficial (Hannis, 2016).

Onshore, Millstone Grit sandstones are encountered (e.g. Cefn-y-Fedw, Gwespyr Sandstone, Aqueduct Grit) in northeast Wales, Lancashire (e.g. Fletcherbank Grit, Pendle Grit and Warley Wise Grit), and in producing East Midland fields (e.g. the Rempstone Oilfield). The Namurian (Marsdenian) depocentre extends from the Staffordshire Gulf, probably to Preston and thins south west under the Cheshire Basin (Collinson et al., 1977; Smith et al., 1995). This pattern continues into the offshore of the East Irish Sea Basin with Namurian absent at the Rhuddlan well on the north Wales coast (Figures 26, 74).

6.1.9.5 The Bowland Shale Formation

The Bowland Shale Formation is not encountered in many wells in the East Irish Sea Basin, however the formation broadly shows an upwards decrease in carbonate turbidites and an increase in siliciclastic sandstone turbidites (Wakefield et al., 2016). Potential thin reservoir sandstones could be found. Well 110/07b- 6 encounters some porous limestone successions up to 15 m thick, although no core samples were taken, the formation was interpreted petrophysically. The limestones have good calculated porosity with an average of 7% and a maximum of 23%. Permeability estimates are poor with an average 0.7 mD and maximum of 16.2 mD (Hannis, 2016).

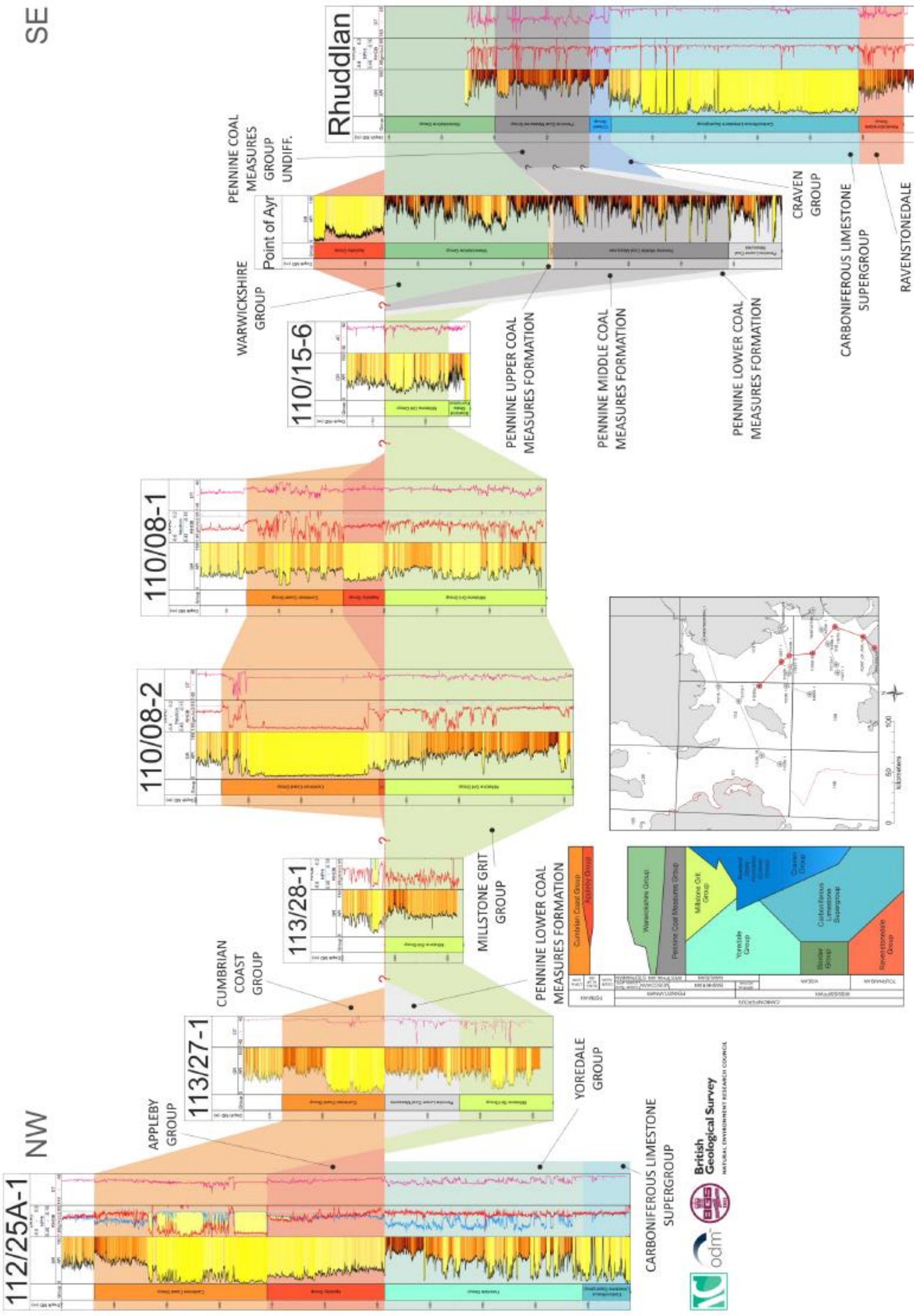


Figure 74 Truncation of Warwickshire Group north of Rhuddlan and condensation of underlying Carboniferous to the south

6.1.9.6 Carboniferous Limestone Supergroup

Carboniferous Limestone Supergroup sequences are interpreted to be widespread over the East Irish Sea Basin and thus are worthy of investigation as a reservoir. Petrophysical analysis of the limestones encountered in 112/25a- 1 appear clean, but have very low matrix porosities to be considered as a reservoir. Accumulations would be hosted in secondary porosity as a result of karstfication or fracturing. Onshore, the Hardstoft Oilfield in Derbyshire produced from the top of the Carboniferous Limestone, but despite numerous shows no further production was established from this reservoir in the East Midlands fields (Falcon and Kent, 1960).

Karstified limestones such as those known from Anglesey (Walkden and Davies, 1983; Figure 75) and apron reefs like those which crop out at Castleton, Derbyshire might be present into the offshore. Waulsortian or knoll reefs of pre-Asbian age may also be possible reservoirs. They are seen at outcrop in the south of the Isle of Man (Dickson et al., 1987) and Craven Basin. Seismic evidence for the possible presence of reefs on the ramp of the Eubonia Tilt-block was described above (Section 5, Figure 37).

Figure 75 Palaeokarst in Carboniferous Limestone on the north coast of Anglesey. BGS photo P201503 BGS©NERC. All Rights Reserved 2016

6.1.10 Seal rocks

Aside from the proven Triassic seals of the Mercia Mudstone Group, the Permian Cumbrian Coast Group provides the most extensive potential seal rock across the whole of the Irish Sea study area. The unit consists of thick evaporites in the north and central East Irish Sea, thinning southward, passing laterally into dolomitic mudstones (Wakefield et al. 2016). It is encountered in wells in every surrounding sub-basin. This seal has yet to be proven to trap significant accumulations of hydrocarbons, although in 112/25a- 1, 113/26- 1, 113/27- 1 and 113/27- 2, there are minor gas shows in the Appleby Group. For the producing East Irish Sea hydrocarbon fields, the fluids migrated out of the Carboniferous and Permian into the Triassic Ormskirk Sandstone reservoir (Colter, 1997).

Carboniferous intraformational mudstone seals have proved adequate in all the onshore fields of the East Midlands (Pharaoh et al., 2011), Cousland in Scotland (Hallett et al, 1985) and offshore Southern North Sea fields (Pletsch et al., 2010), and can be expected to work in the Irish Sea basins as well. Evaporites are known in early Carboniferous sequences of the Pennine Basin (e.g. Tournaisian in Hathern borehole, Pharaoh et al. 2011) however their sealing capacity is not proven and is only of interest if significant faults offset above the younger Carboniferous source. Intraformational mudstone seals are possible within the heterolithic Yoredale, Millstone Grit and Coal Measures units, though lateral continuity and mudstone thickness are likely to prove a risk.

6.1.11 Summary- East Irish Sea Basin evolution and petroleum systems

The main important events in the development of the East Irish Sea Basin, with relevance for petroleum systems are:

1. Visean-Namurian Carboniferous rifting on NE-SW trending faults resulted in depocentres which accumulated marine shale source rocks, preceeding regional thermal subsidence. The Bowland Shale Formation forms the main source rock interval.
2. Millstone Grit Group and Bowland Shale Formation contain thin clean sandstones which could be considered potential reservoirs, if not compacted by burial to tight sandstones.
3. Bowland Shale Formation source rocks are buried deeply to depths of over 7 km under the Keys Basin. Potentially prospective areas may exist at depth adjacent to the Keys Basin, and west of the Keys Fault in blocks 110/1 and 113/26. 112/30-1 would seem to be a very shallow and unsatisfactory test of this potential system (Figure 21).
4. Shales within the Millstone Grit Group and Pennine Coal Measures have the potential to act as a secondary source rock, when present and buried deep enough to achieve maturity.
5. Late Carboniferous (Millstone Grit and Pennine Coal Measures) sedimentation shows marked thinning to the south. There is thinning towards the north, in places, but the basin margin appears to be a set of faults. Burial by Late Carboniferous sediments likely resulted in early maturation of hydrocarbons in these source rocks in the deepest basins, but probably resulted in the destruction of reservoir porosity and permeability in the depocentres due to compaction.
6. Some onshore exposures show evidence of a Pre-Warwickshire Group unconformity, though other onshore exposures are conformable (Wakefield et al., 2016). The regional significance is that there could have been erosion of the Late Carboniferous depocentre. Warwickshire Group sedimentary rocks were not so deeply buried, and are likely to retain better reservoir characteristics, these are seismically interpreted but have yet to be proven offshore.
7. The Variscan Orogeny caused uplift, folding and thrusting. Inversion also occurred on faults which became important syn-sedimentary faults in the Permian. Deposition of Permian Appleby and Cumbria Coastal groups resulted in a possible reservoir - seal combination overlying the Carboniferous source rocks.
8. Permo-Triassic rifting is along NNW-SSE or N-S trends. These faults cut across the main Carboniferous structures and have allowed late Cretaceous–early Cenozoic vertical migration of Carboniferous-sourced hydrocarbons into Triassic reservoirs. A migration route to the Triassic reservoir in the centre of the East Irish Sea Basin is coincident with a zone where the Warwickshire and Appleby groups have been removed.

Potential plays exist in ‘Marginal’ areas surrounding the ‘Main Graben’;

9. The Ribble Estuary Inlier east of the Formby Point Fault (Figure 16) is a candidate for a working petroleum play. It lies adjacent to the deep Deemster Basin where there is a thick sequence of Late Carboniferous sedimentary rocks preserved, and between the Triassic Formby and Lennox fields.

10. More widely the belt of Variscan inversion structures correlated with structures on the Formby Platform, and Ribbledale Foldbelt onshore (Figure 15), from which hydrocarbons have leaked into the overlying, Ormskirk-hosted Hamilton fields may offer potential. The biggest risk here is whether reservoirs remain unbreached at the Pre-Permian level, and retain good poroperm characteristics at depths of about 2500 m.
11. To the west, a potential play exists sourced from the deep Godred Croven Basin drilled by 110/11- 1 (Figure 5) to the Carboniferous strata on the faulted highs of its flanks. The Ormskirk Sandstone is very shallow in these locations but the Carboniferous strata might be securely sealed by the Cumbrian Coast Group.
12. The thick Westphalian sequences preserved in the Eubonia Tilt-Block in Quadrant 109, outside the main Permian-Mesozoic graben system and unaffected by Cenozoic inversion offer potential. The presence and quality of seals form a major risk as the Cumbrian Coast Group seal is thin or absent and Carboniferous intraformational seals are required but untested. Based on the limited dataset available in adjacent basins, reservoir quality is also a significant risk.
13. A more speculative play lies in the extensive carbonate platform interpreted in Quadrant 109 and surrounding the Isle of Man, in reefal facies with enhanced secondary porosity. Here, source rock presence and migration pathways, reservoir properties and seal quality are major risks.

6.2 SOLWAY FIRTH BASIN

The Permian – Jurassic Solway Firth Basin, linked north-east to the Carlisle Basin and south-west to the Peel Basin is underlain by a Carboniferous basin of the same trend, an extension of the Northumberland Trough (Chadwick et al., 1995; Figure 40). Two well penetrations (112/15-1 and 112/19-1) prove a Visean – Namurian Yoredale Group distinguished from the Carboniferous Limestone Supergroup by the presence of fewer carbonates.

The Yoredale Group sandstones, limestones and siltstones represent a fluvio-deltaic depositional environment (see Wakefield et al., 2016) which is a lateral equivalent of the of basinal Bowland Shale facies. That is, the Bowland Shale Formation is not proven in the Solway Firth Basin (Figures 40, 41, 42). In the onshore Cumberland Coalfield, coals are gassy (Jones et al., 2004) but the Coal Measures have not been drilled offshore in this basin.

Potential Carboniferous reservoir intervals include a relatively small area of Warwickshire Group on both sides of the Maryport Fault (Figures 40, 42, 43), and the Fell Sandstone in the main part of the basin.

Intraformational silts and shales within the Yoredale Group could provide seals above potential reservoir sandstones. Where present the Cumbrian Coast Group provides a thin seal of halites, claystones and anhydrites, which thickens towards the south.

6.3 PEEL BASIN

The Peel Basin is a Permo-Triassic basin lying between the Isle of Man and Northern Ireland, partly underlain by a Carboniferous basin. Wells 111/25a- 1 and 111/15- 1 penetrated the Carboniferous Limestone Supergroup, in contrast to the Yoredale Group encountered in the along-strike, Solway Basin. The lack of a clastic, fluvio-deltaic system may enhance the likelihood of the Bowland Shale (source rock) equivalent between 111/25a-1 and the Isle of Man coast, but there is no data to test this hypothesis. The basin may extend to the Carlingford Lough area near the Ireland–Northern Ireland border. BGS boreholes (in Quadrant 212, near the Irish coast) 73/65 and 73/67 are probably of Visean age forming a rim to the Lower Palaeozoic Longford-Down Massif. BGS borehole 71/43 near the Isle of Man coast was dated as Namurian. The Permian sequence is thin and unlikely to provide an effective seal, but the Mercia Mudstone Group provides a good regional caprock. The data available precludes evidence of a working petroleum system in the Peel Basin (see also Figure 46).

6.4 THE NORTH CHANNEL BASIN TO SOUTH-WEST ARRAN TROUGH

The North Channel is a NW-trending Permo-Triassic basin lying between the Southern Uplands and the Longford-Down Massif of Northern Ireland and forms the main rift through the massif. Several smaller basins lie parallel in Scotland (Stranraer, Lochmaben) and Ireland (Strangford Lough). The underlying strata are probably Devonian, although the seismic is poorly resolved because the only well (111/15-1) passed through the boundary fault adjacent to the Southern Uplands, missing the Carboniferous section (further discussion in Section 5). Data is lacking for the presence of source, reservoir and seal in this area.

Permo-Triassic and underlying Devonian and Carboniferous basins are present onshore in Northern Ireland and are interpreted in the South-West Arran Trough to Firth of Clyde. As there are no offshore wells, interpretation rests heavily on the sequence in Larne 2 borehole in Northern Ireland in which the basal volcanics were interpreted as Permian (Penn et al., 1983) and on extrapolation from Arran and the Midland Valley of Scotland. The lack of data results in a low confidence to interpretations made offshore.

Onshore in the Midland Valley of Scotland and in Northern Ireland a range of potential Carboniferous source rocks (coals, carbonaceous mudstones) and sandstone reservoir intervals are documented, though there is considerable spatial variability (Browne et al. 1999; Underhill et al. 2008; Reay, 2004; 2012). Seismic interpretation offshore has tentatively included a Carboniferous succession buried to 4000 m (Figure 55) and with faulting and folding observed offering potential for structural traps. However the interpretation is poorly constrained by data, precluding the knowledge to assess petroleum system elements.

Onshore in Northern Ireland, a conventional Carboniferous prospect is planned to be drilled in Woodburn Forest. Brief mention is made of the Rathlin Trough, which lies outside the region of study, and for which only limited seismic data covering the offshore extension of the Machrihanish Coalfield have been examined. The source rocks include coals and oil shales (Murlough Bay Formation) of Lower Carboniferous age which have excellent TOC and which are mostly in the oil window, with smaller areas in the gas window (Reay, 2012).This sequence together with volcanic rocks invites comparison with the Lothian part of the Midland Valley of Scotland. Drilling took place in the Machrihanish Coalfield in Westphalian rocks, at Magilligan in the west of the basin and at Ballinlea in 2008. At the latter well, oil was produced from the Carrickmore Formation sandstones (Providence, 2013) of the wide Visean subcrop (Smith, 1985), but the well is unreleased, so no further details are available.

7 Petroleum system knowns and risks

Figures 76, 77 and 78 summarise the petroleum systems elements across the Irish Sea study area. They highlight the laterally variability in the Carboniferous basin fill and level of Varsican erosion.

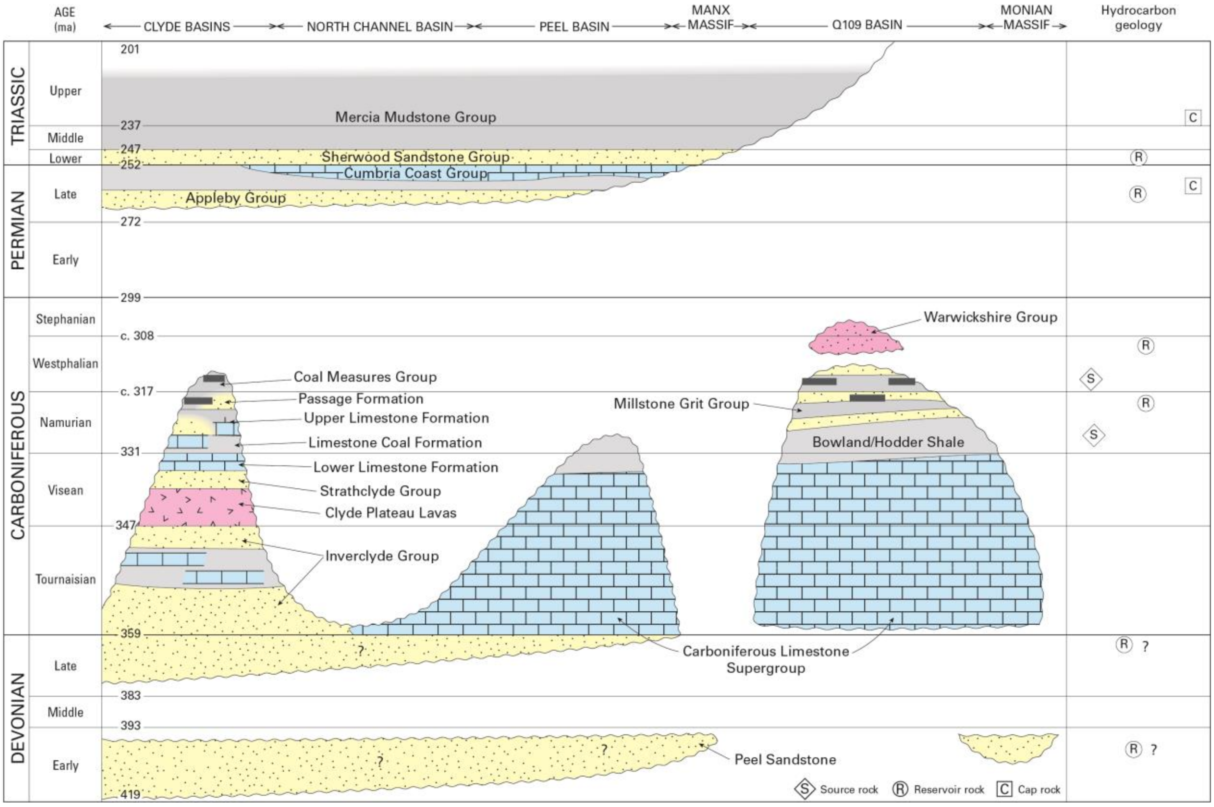


Figure 76 Petroleum system elements in a north-south transect across the western part of the region.

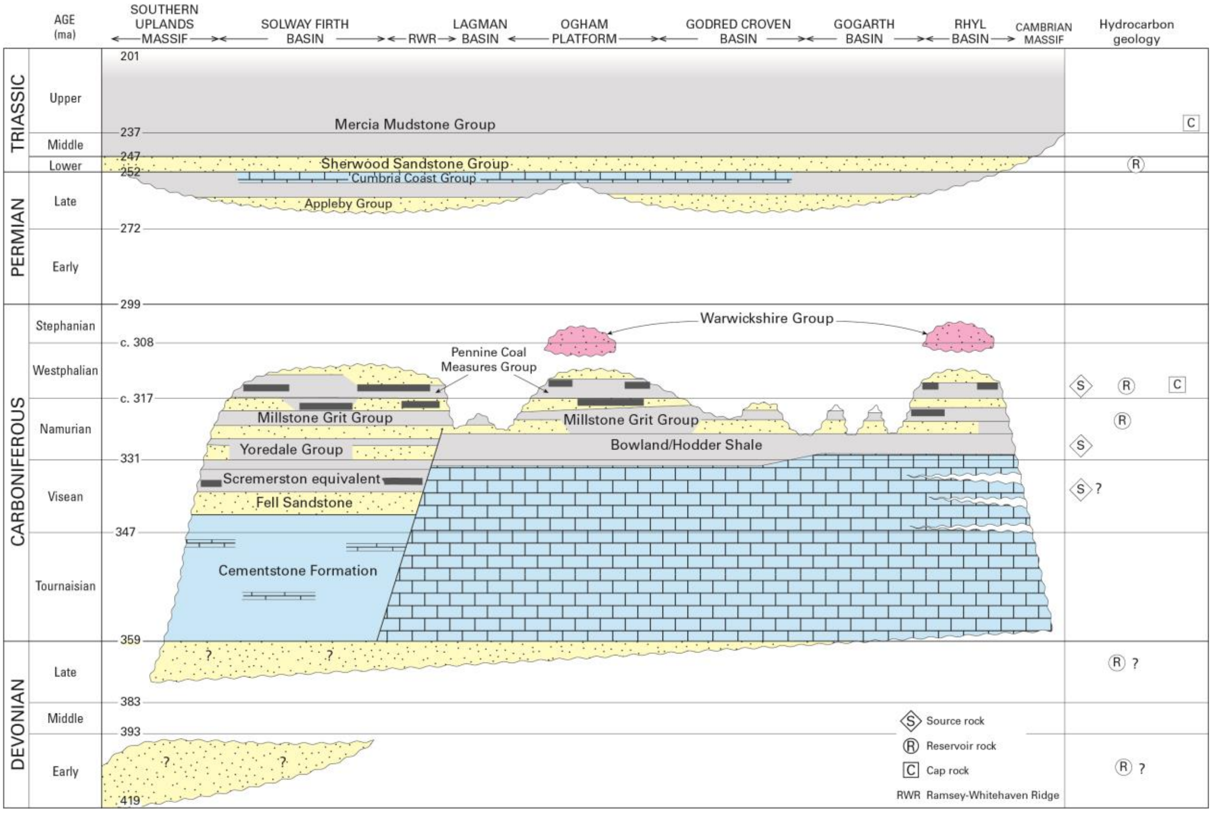


Figure 77 Petroleum system elements in a north-south transect across the central part of the region.

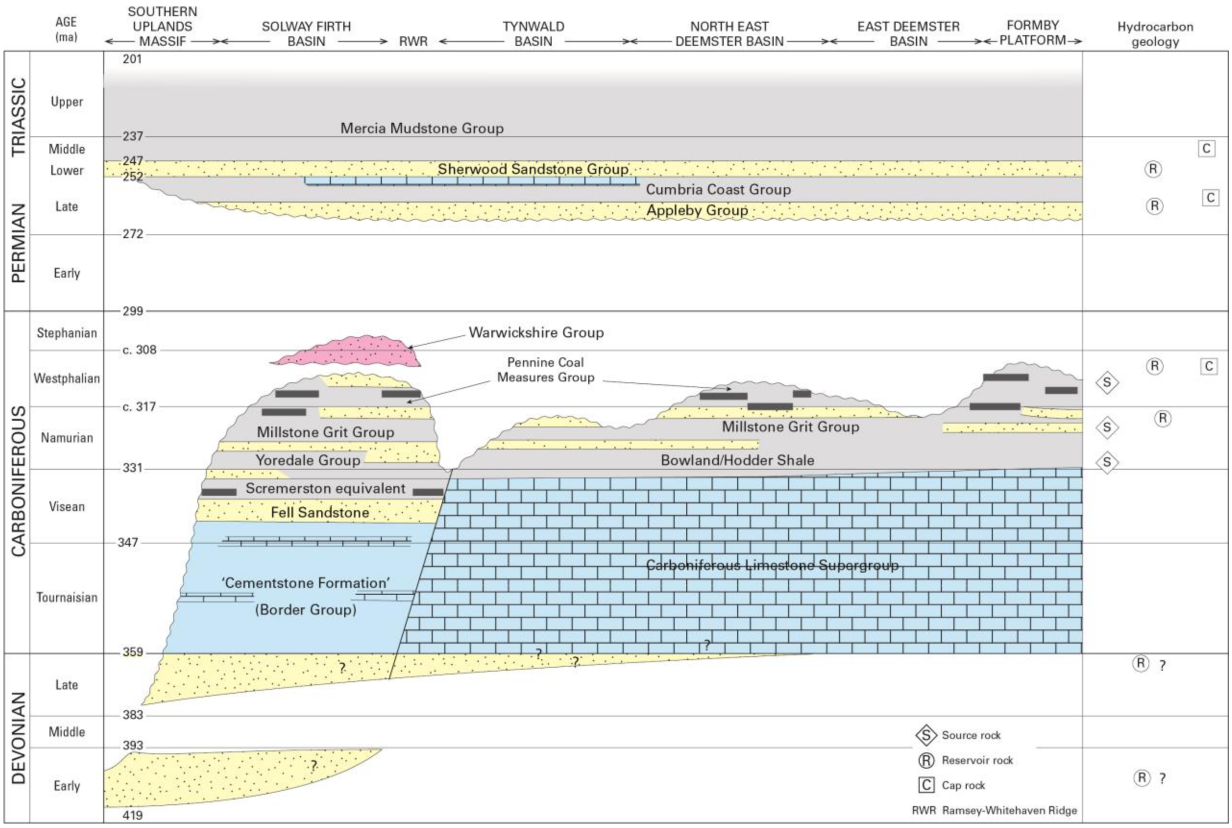


Figure 78 Petroleum system elements in a north-south transect across the eastern part of the region.

Knowns and risks are summarised in map form at regional scale on Figures 79-83 using a traffic light scheme. Lighter colours represent greater uncertainty due to lack of constraining data.

The widespread distribution (Figure 79) of the principal Namurian source rock (Bowland Shale Formation) is constrained by borehole penetrations in the East Irish Sea Basin, but the absence of boreholes in the deepest part of the basin (Keys and Lagman basins) and onto the Manx-Furness Ridge means that the northern limit is poorly constrained. The nature of the transition to the Solway Firth and Northumberland basins, where boreholes prove Yoredale facies (Figures 42 and 43) is therefore poorly known. By analogy with the adjacent onshore, Namurian source rocks may also be present in the Clyde basins and adjacent North Channel Basin, but are unlikely to be present in the southern part of the latter, or in the Peel Basin (Figure 46). Attenuation of the Namurian sequence southwards towards the Welsh Massif also increases the source risk in this direction. The paucity of data on the maturity of the source means that this parameter cannot be mapped in detail and Figure 79 reflects only the *presence* of a Carboniferous source rock.

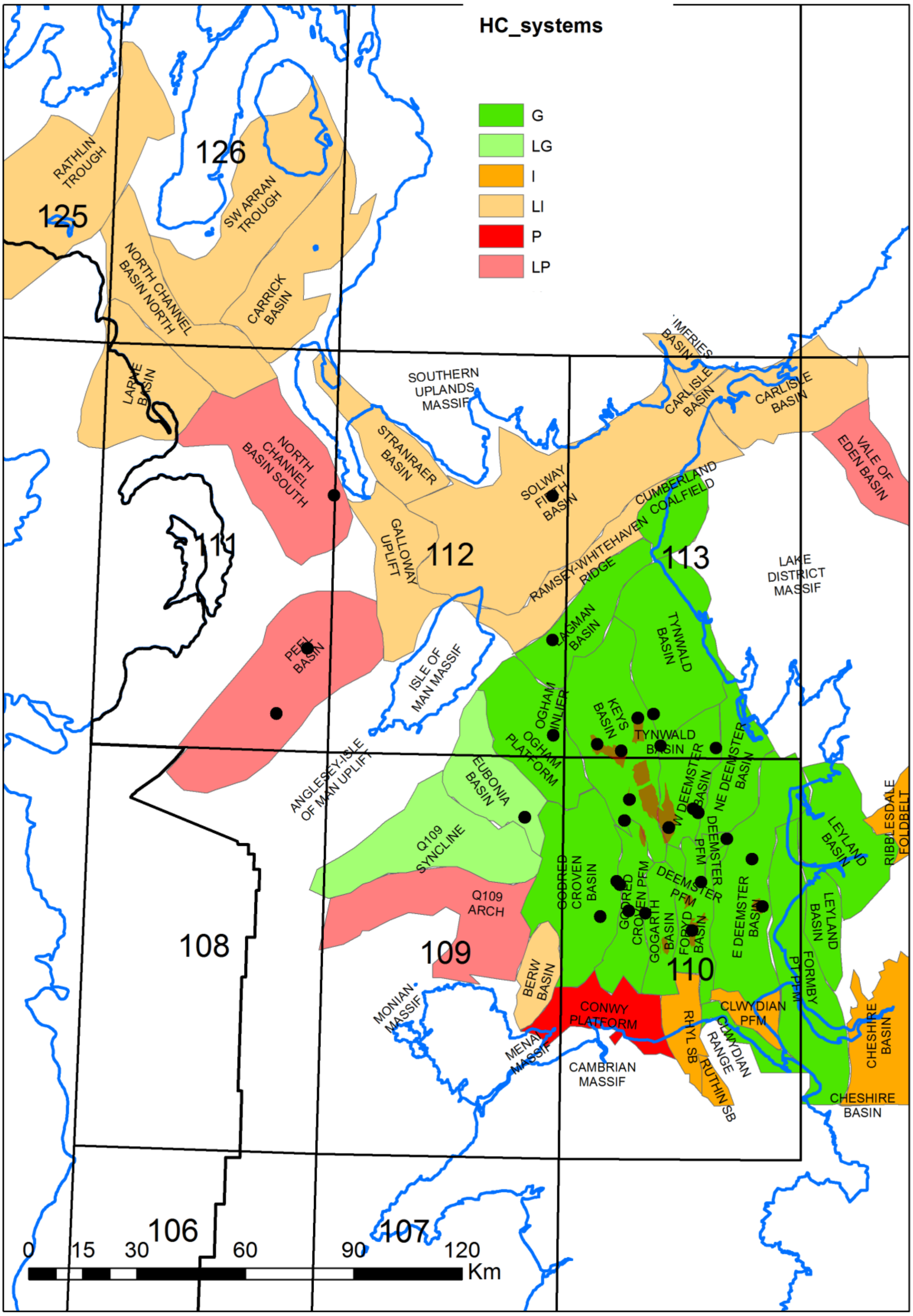


Figure 79 Risk map giving a regional indication of likely Carboniferous source rock extent/presence. Note that source rock quality, thickness and maturity are not incorporated. Key: G=Low (supported by data); LG=Low (inferred); I=Intermediate (supported by data); LI=Intermediate (inferred); P=High (supported by data); LP=High (inferred). Location of DECC fields (brown) and key Carboniferous well penetrations (plus 111/15- 1; black dots) are also shown. Lighter colours are inferred and have greater uncertainty.

Similarly, the reservoir porosity-permeability characteristics are poorly known over large parts of the region studied. The available data indicates that Carboniferous sandstones beneath the Morecambe fields have poor porosity and permeability (Centrica, 2015 pers. comm.). This is no doubt a consequence of their deep burial, and processes such as platy illite development and silica cementation which affect even the overlying Triassic formations (Colter, 1989 Bushell, 1986; Woodward and Curtis, 1987; Cowan, 1991; Stuart, 1993). The velocity analysis carried out by Pharaoh et al. (2016a) as part of the seismic depth conversion exercise indicates that certain areas marginal to the Main Graben, may not have suffered such deep Permian-Mesozoic burial and may therefore retain slightly better poroperm characteristics. Very few data are available however, so for caution, Figure 80 shows most of these areas with ‘intermediate’ values, at best. Extensive carbonate platforms (Peel Basin, Quadrant 109 Syncline, Section 5) surrounding the Isle of Man also have unknown poroperm characteristics. Until more is known about possible secondary porosity (following de-dolomitisation) and fracture density, the reservoir properties of these areas are ranked as high risk.

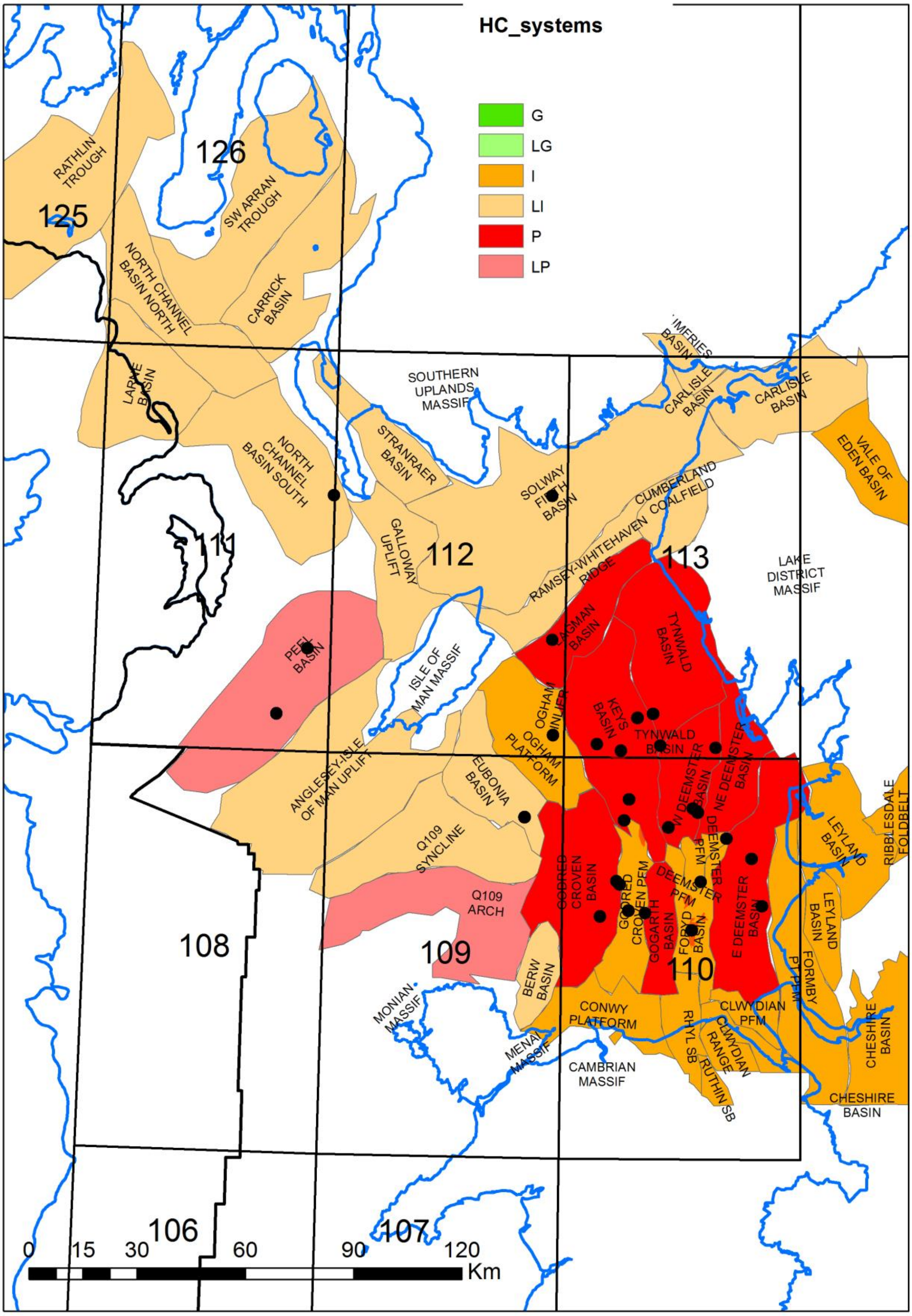


Figure 80 Risk map giving a regional indication of likely Carboniferous porosity-permeability risk. Key: G=Low (supported by data); LG=Low (inferred); I=Intermediate (supported by data); LI=Intermediate (inferred); P=High (supported by data); LP=High (inferred). Location of DECC fields (brown) and key Carboniferous well penetrations (plus 111/15- 1; black dots) are also shown. Lighter colours are inferred and have greater uncertainty.

The seismic interpretation carried out in this project has identified numerous previously undescribed ‘structural zones’ in which potential traps may be developed (Figure 81). These include Variscan inversion anticlines of two generations, and Cenozoic inversion structures which often developed by continued growth of the Variscan structures. Areas with newly recognised structures in Quadrant 109, the Eubonia Basin and Godred Croven Basin and Platform, all require more detailed seismic investigation to establish trap geometry and integrity. Figure 81 reflects the distribution of the inversion structures interpreted on seismic data.

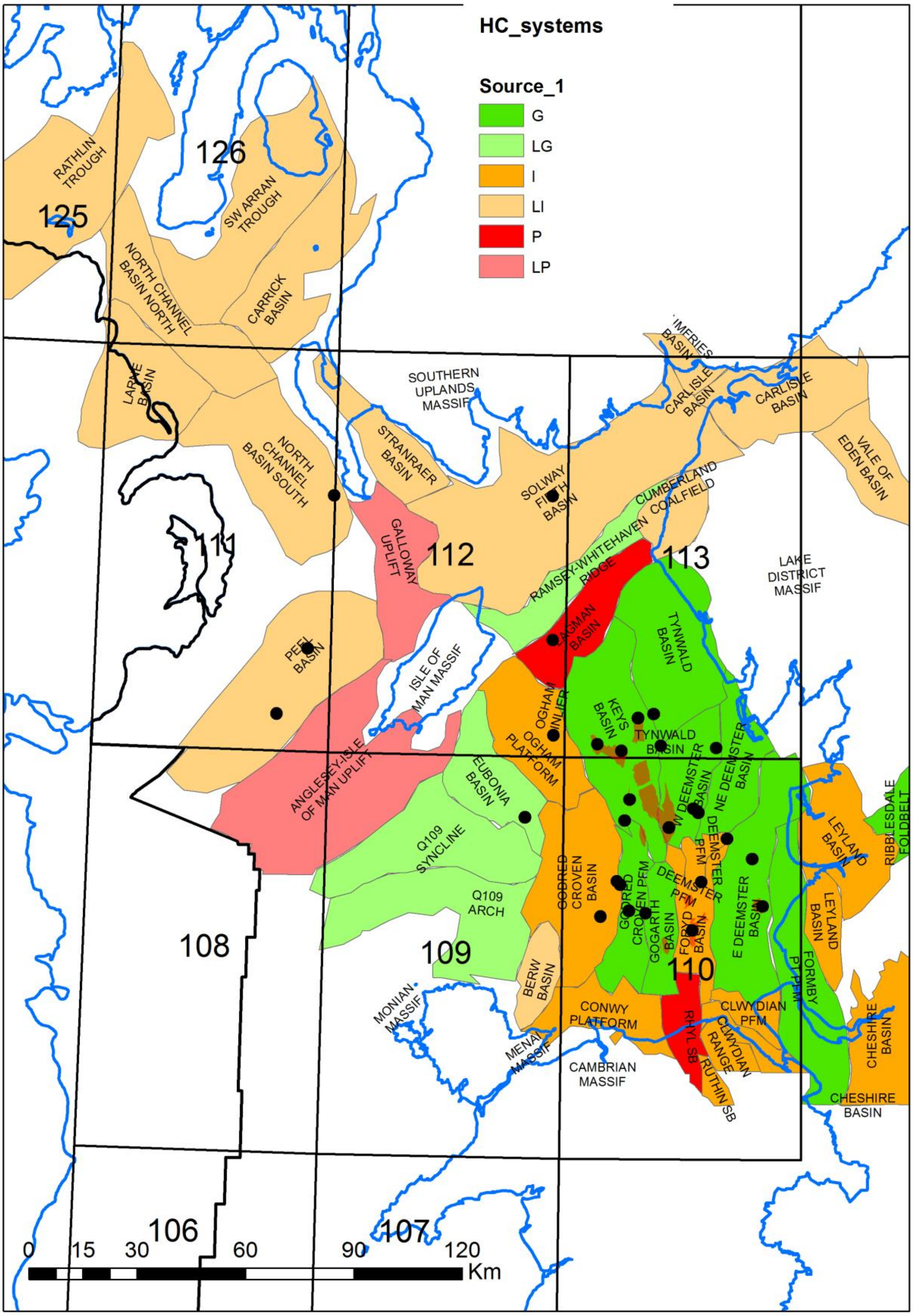


Figure 81 Risk map giving a regional indication of likely presence of Carboniferous structural traps related to Varsican inversion structures (any potential traps require more detailed seismic mapping to determine dip closure and integrity). Key: G=Low (supported by data); LG=Low (inferred); I=Intermediate (supported by data); LI=Intermediate (inferred); P=High (supported by data); LP=High (inferred). Location of DECC fields (brown) and key Carboniferous well penetrations (plus 111/15- 1; black dots) are also shown. Lighter colours are inferred and have greater uncertainty.

A good seal and caprock (Mercia Mudstone Group) is present throughout the East Irish Sea Basin but is absent across many of the margins of the Main Graben (Figures 82, 83). Unfortunately the potential seal of the Permian Cumbrian Coastal Group sequence thins and fails in the same directions. In the Main Graben a relatively thick shale and evaporite (St Bees Evaporites, Cumbrian Coastal Group) may be developed. The same is true in the North Channel and Larne Basin, where several Triassic halites are present. In general, seal is considered to represent the most significant risk in the hydrocarbon system at the margins of the East Irish Sea Basin. Yet-to-find reservoirs are anticipated to be relatively small in volume and with shallow column heights supported by intra-formational seals.

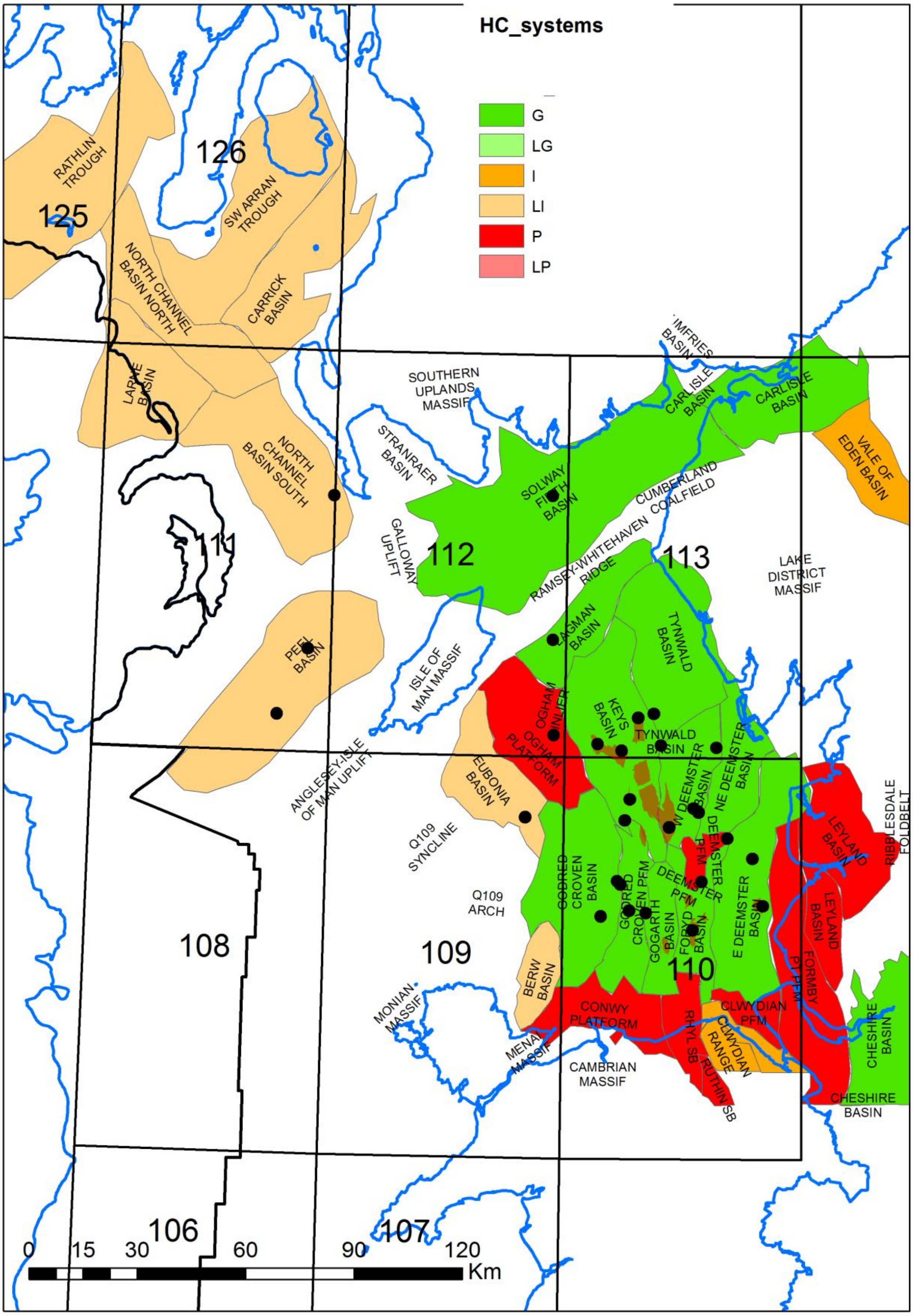


Figure 82 Risk map giving a regional indication of likely presence of Permian seals within the Cumbrian Coastal Group (evaporites, mudstones). Key: G=Low (supported by data); LG=Low (inferred); I=Intermediate (supported by data); LI=Intermediate (inferred); P=High (supported by data); LP=High (inferred). Location of DECC fields (brown) and key Carboniferous well penetrations (plus 111/15- 1; black dots) are also shown. Lighter colours are inferred and have greater uncertainty.

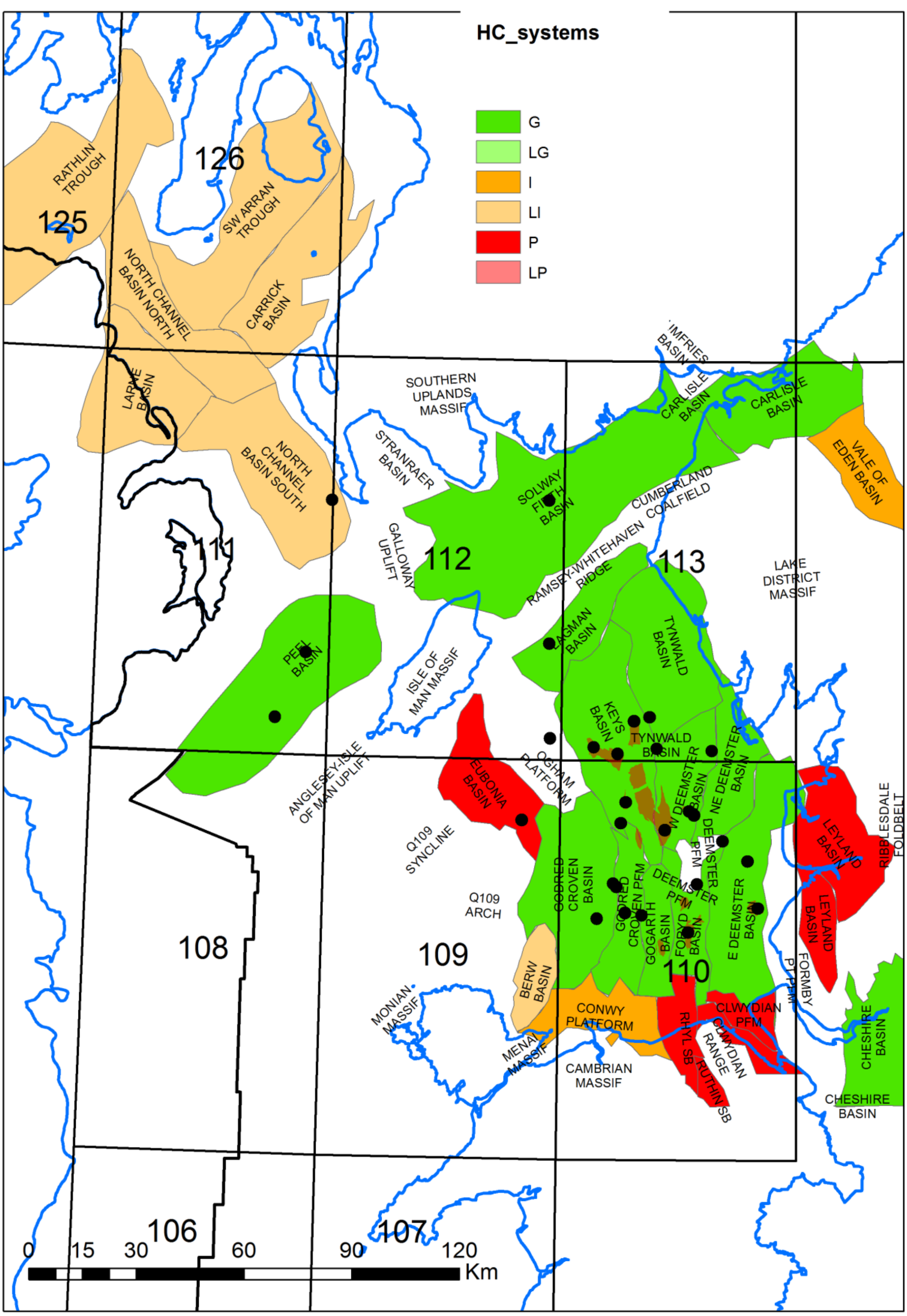


Figure 83 Risk map giving a regional indication of likely presence of a thick Triassic cap rock (Mercia Mudstone Group). Key: G=Low (supported by data); LG=Low (inferred); I=Intermediate (supported by data); LI=Intermediate (inferred); P=High (supported by data); LP=High (inferred). Location of DECC fields (brown) and key Carboniferous well penetrations (plus 111/15- 1; black dots) are also shown. Lighter colours are inferred and have greater uncertainty.

From the analysis of the seismic data, integrated with well, core data etc, it is considered that the Marginal Graben and platform areas hold the greatest potential for undiscovered hydrocarbon resources in the Carboniferous, although the geochemical, petrophysical and other essential data are scant.

The most prospective parts of the region, outside the Ormskirk conventional gas play, are considered to be:

- The thick Westphalian sequences preserved in the Eubonia Tilt-Block in Quadrant 109, outside the main Permian-Mesozoic graben system and unaffected by Cenozoic inversion. The presence and quality of seals form a major risk as the Cumbrian Coast Group seal is thin or absent and Carboniferous intraformational seals are required but untested. Based on the limited dataset available in adjacent basins, reservoir quality is also a significant risk.
- A belt of Variscan inversion structures correlated with structures on the Formby Platform, and Ribbledale Foldbelt onshore, from which hydrocarbons have leaked into the overlying, Ormskirk-hosted Hamilton fields. The biggest risk here is whether reservoirs remain unbreached at the Pre-Permian level, and retain good poroperm characteristics at depths of about 2500 m.
- A more speculative play lies in the extensive carbonate platform in Quadrant 109 and surrounding the Isle of Man, in reefal facies with enhanced secondary porosity. Here, source rock presence and migration pathways, reservoir properties and seal quality are major risks.

8 Recommendations for further work

Numerous complementary or detailed studies have been out with the time and resource of the 21CXRM Palaeozoic Roadmap project. Where data allows, studies such as, compilation and interpretation of petrographical data for example for diagenesis studies for reservoir quality etc., as well as new analysis e.g. apatite fission track for burial history or additional Rock-Eval, vitrinite reflectance and biomarker analyses, would add greatly to more detailed interpretations. There are however some more fundamental themes that it would be beneficial to consider for future work:

- Regional study of the late Permian Cumbrian Coast Group – critical reservoir and seal intervals for the Carboniferous plays
- Tight gas, intraformational seals, stratigraphic traps within the lower–mid Carboniferous basinal play
- Detailed mapping of the Intra-Namurian and Top Namurian picks, which are the key to understanding the geometry of Variscan inversion structures. This was not possible during this rapid reconnaissance regional study
- Further work linking the onshore and the nearshore, perhaps with a focus on unconventionals and tight gas
- New seismic acquisition to include a denser network of 2D in Quadrant 109, and a patch of 3D south of the Isle of Man to map the key Variscan inversion structures there.
- A more thorough analysis of petrophysical data is needed to examine possible contrasts in Carboniferous poroperm characteristics outside the Main Graben
- Section balancing to analyse the magnitudes and vectors of the multiple phases of inversion recognised from the seismic study

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