An overlooked play? Structure, stratigraphy and hydrocarbon prospectivity of the Carboniferous in the East Irish Sea-North Channel basin complex

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Abstract: Seismic mapping of key Palaeozoic surfaces in the East Irish Sea – North Channel region has been incorporated into a review of hydrocarbon prospectivity. The major Carboniferous basinal and inversion elements are identified, allowing an assessment of the principal kitchens for hydrocarbon generation and possible migration paths. A major Carboniferous tilt-block is identified beneath the central part of the (Permian to Mesozoic) East Irish Sea Basin (EISB), bounded by carbonate platforms to south and north. The importance of the Bowland Shale Formation as the key source rock is reaffirmed, the Pennine Coal Measures having been eroded over wide areas as a result of Variscan inversion and erosion prior to Permian deposition. Peak generation from the Bowland source rock coincided with maximum burial of the system in late Jurassic/early Cretaceous time. A multiphase history of Variscan inversion has generated numerous structural traps whose potential remains essentially unexplored. Leakage of hydrocarbons from these into the overlying Triassic Ormskirk Sandstone reservoirs is likely to have occurred on a number of occasions, but currently unknown is how much resource remains in place below the Base-Permian unconformity. Poor permeability in the Pennsylvanian strata beneath the Triassic fields is a significant risk; the same may not be true in the less deeply buried marginal areas of the EISB, where additional potential plays are present in Mississippian carbonate platforms and latest Pennsylvanian clastic sedimentary rocks. Outside the EISB, the North Channel, Solway and Peel basins also contain Devonian and/or Carboniferous rocks. There have however been no discoveries, largely a consequence of the absence of a high quality source rock and a regional seal comparable to the Mercia Mudstone Group and Permian evaporites of the Cumbrian Coast Group in the EISB.

The productive oil and gas fields of the EISB evidence a working, Carboniferous-sourced petroleum system. Whilst a great deal may be known of the Triassic reservoir and seal (Meadows *et al.* 1997), little is known about Carboniferous and Permian petroleum systems at depth and in adjacent basins, that may offer significant additional potential. Following the Wood Review (2014), Palaeozoic plays, including that of the greater Irish Sea area were identified as priority for building regional digital datasets and stimulating exploration. In response, the *21st Century Exploration Roadmap: Palaeozoic Project* running from 2014-2016 and openly released in 2017, undertook regional scale seismic and well interpretation, source and reservoir screening studies and basin modelling. This paper provides a re-interpretation of the structural history of the greater Irish Sea, and its influence on potential Carboniferous and Permian prospectivity including the marginal basins.

The Carboniferous structure and stratigraphy of the UK sector of the East Irish Sea-North Channel region has been reviewed using all available well and seismic reflection data. The project interpreted about 40,000 km of 2D seismic data of many vintages from 1980-2000, with local infill from

3D data, to generate time and depth-converted surfaces for key Palaeozoic surfaces (Pharaoh *et al.* 2016a). Priority was given to the interpretation of long regional speculative lines, with infill from licence- and prospect-scale surveys. These surfaces were then used as the basis for an assessment of Palaeozoic hydrocarbon prospectivity (Pharaoh *et al.* 2016b), which forms the core of this paper. For brevity, the seismic interpretations are summarised using synoptic diagrams ('cartoons'). The present economic focus of the hydrocarbon province is the Morecambe Bay gasfield and its satellites, located within the EISB, a basin complex of Permian to Mesozoic age comprising a number of mainly N-S oriented graben and intervening platforms (BGS 1994; Jackson *et al.* 1987, 1995, 1997). The principal structures of the EISB are strongly discordant to those in the pre-Permian substrate however, which bear the imprint of a long and complex evolution culminating in the Variscan Orogeny in latest Carboniferous time. For these Devonian and Carboniferous tectonic elements, a new terminology is presented here and the lithostratigraphical nomenclature of Waters *et al.* (2011) is used to integrate onshore and offshore successions, allowing more precise correlation than the scheme introduced by Jackson *et al.* (1997)..

The Bowland Shale Formation is recognised as a prolific source of gas for the Permo-Triassic reservoirs (Armstrong *et al.* 1997), but potential Namurian and Westphalian reservoirs suffer from low porosity and permeability due to the combined effects of Variscan inversion, deep burial in a Permian-Mesozoic rift, Cenozoic inversion, magmatism and thermal effects associated with the rifting of the North Atlantic (Meadows *et al.* 1997; Quirk & Kimbell 1997). Several areas on the margins of the EISB (Manx-Furness Ridge, Cumbrian margin, Fylde margin, Cambrian margin) are underlain by the offshore extensions of onshore coalfields or Namurian strata. These areas are covered in some detail by seismic data, and the availability of onshore analogues allows a more realistic assessment in terms of potential for development of non-conventional resources, perhaps from coastal locations.

Methodology and datasets

The exploration datasets used in the regional interpretation are depicted in Fig. 1. The 2D seismic datasets include regional speculative data supplied by geophysical companies (CGG, IHS and WesternGeco); licence- and prospect-level datasets provided by the Common Data Access Initiative (CDA) offshore and United Kingdom Onshore Geophysical Library (UKOGL) nearshore and onshore; and data supplied directly by participating companies (Centrica plc). The 3D dataset used was supplied by CDA, augmented by data from the 3D Terracube supplied by CGG. The well picks were supplied from the DECC well database at BGS Edinburgh, with further interpretation during the project. Wells used in the petrophysical analysis are highlighted with a circle.

Pre-Carboniferous structural evolution

The crust of the southern part of the region (North Wales, Anglesey and adjacent offshore areas (Fig. 2) was generated as volcanic and sedimentary complexes in magmatic arc-trench systems during late Proterozoic time. Many early tectonic lineaments (e.g. the Menai Strait Fault Zone; Gibbons 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 in 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 (Smith *et al.* 1999; Chew & Strachan 2014). Its southern limit is marked by the Highland Boundary Fault, which forms the northern boundary of the area of investigation.

The crust in the central part of the region 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 (Bluck 2002; Barnes *et al.* 2006; Chew & Strachan 2014). 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 (Barnes *et al.* 2006); the numerous accretionary tracts of the Southern Uplands massif (Bluck 2002); and numerous faults with this trend within the Southern Highlands terrane (Chew & Strachan 2014).

In this study, a NW-dipping zone of enhanced reflectivity in pre-Carboniferous 'basement', previously referred to as the Barrule Thrust (Chadwick *et al.* 2001), was mapped over a large area to NW of the Isle of Man. The analysis of the deep seismic reflection data presented by England & Soper (1997) suggests that this structure lies within the Avalonian footwall of the Iapetus Suture, rather than representing the suture itself. A further zone of NNW-dipping basement reflectivity underlies the southern part of the EISB (Jackson & Mulholland 1993; Pharaoh *et al.* 2016a' 2016b), being particularly prominent beneath the Conwy Platform, just off the north coast of Wales (Fig. 2). The dip of this zone steepens as it approaches the coast, and it is inferred to correlate with the southernmost strands of the Menai Strait Lineament, i.e. the Menai and Dinorwic fault zones. Although the seismic coverage is relatively poor in this area, the available data suggest that this zone represents the deepest regional detachment, with all subsequent extensional faulting (of Carboniferous and Permian-Mesozoic age) penetrating no deeper into the crust.

During the Acadian phase of the Caledonian Orogeny, most 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 (Chew & Strachan 2014). 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, in the Midland Valley and form the molasse to the Caledonian Orogen (Trewin & Thirlwall 2002). In the south (Anglesey), Devonian strata are more limited in development and related to local faulted basin margins (Hillier & Williams 2006). In this tectonic regime, W-E extension is anticipated (Coward 1993). 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 rift basins (North Channel, Stranraer, Carlingford Lough) within the Southern Uplands Massif, and the Peel Sandstone Graben of the Isle of Man (Maddox *et al.* 1997; Parnell 1997; Quirk & Kimbell 1997).

Carboniferous structural and stratigraphic evolution

An extensional- transtensional tectonic regime persisted into Carboniferous time (Leslie *et al.* 2016). Although a general W-E extensional regime has been invoked in Mississippian time (Coward 1993), 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 Paola *et al.* 2005). This 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.* 1995), and is controlled by major bounding faults on a SW-NE trend. The Peel Basin along strike to the SW, has a similar trend but opposite structural polarity and a very different basin setting in the Carboniferous (Fig. 2). 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 extensional basins

The Carboniferous substrate of the EISB comprises a number of basin elements, comparable to that of the UK onshore. Fig. 2 presents a speculative reconstruction of the principal tectonic elements in

Mississippian time. It is based heavily on seismostratigraphic and structural interpretation, as only five offshore boreholes penetrate Visean strata in the whole of the province (112/25a-1 and 113/27-2 in the EISB; 111/25-1A and 111/29-1 in the Peel Basin; and 112/19-1 in the Solway Basin, Fig. 2). In the centre of the EISB, a major basin, here referred to as the Eubonia Tilt-Block (Fig. 2), is inferred to extend from the Quadrant 109 (Q109) Syncline in the SW (BGS 1994) to the Ogham Platform (Fig. 2). Extension farther east, beneath the Lagman and Tynwald (Permian-Mesozoic) basin of the EISB, towards the western edge of the Lake District, is also inferred. The presence of a major half-graben (tilt-block), controlled by a major syndepositional bounding fault on its NW margin, the Eubonia-Lagman Fault System (Fig. 2, 3a), is indicated by the seismic reflection data. The structure was not identified as a tilt-block by Jackson & Mulholland (1993; p800), but they did recognise the marked asymmetry of the northern limb of the Q109 Syncline/Basin and the presence of up to 7.5 km of Visean to late Westphalian (and possibly Stephanian) strata. Fig. 3a shows a seismic line extending SE with up to 7.5 km of Visean to late Westphalian (and possibly Stephanian) strata from the Isle of Man towards Anglesey (Fig. 2). It demonstrates the presence of over 2.5 s Two-Way Travel Time (TWTT) of Carboniferous strata east of the Eubonia Fault, in what is referred to as the Eubonia Tilt-block (Pharaoh *et al.* 2016b). Poor well control is provided by a few distant wells on the western edge of the EISB (Fig. 2) and the picks are not well constrained

Towards the top of the tilt-block in the south, on the Holy Island Shelf, brighter reflectivity in the upper Visean interval, may represent the development of reefal carbonates. The southern end of the section crosses a northward-vergent inversion anticline-thrust couple, defining the northern limit of the Môn-Deemster Fold Belt. This is a 25 km wide belt of strong Variscan inversion, extending ENE from the north coast of Anglesey, from the Q109 Arch to the Deemster Platform (Fig. 2). The internal structure of this belt is imaged on numerous N-S profiles crossing the Godred Croven Basin, and Fig. 3b, an arbitrary line through 3D data in this area, is representative. A schematic profile is presented in Fig. 4b. A series of parallel WSW-ENE trending anticlinal folds has been mapped through the area. The internal structure of this inversion belt is complex, comprising a fan-like array of anticlines and synclines with associated thrusts, SSE-vergent in the south, and NNW-vergent in the north (Fig. 4b). Fig. 3b clearly shows discordant reflections in the Visean sequence, extending down into the Caledonian basement, interpreted here as fault-plane reflections. Below 3s TWTT, a further zone of intra-basement reflectivity is interpreted as a deeper Caledonian detachment surface, as recognised by Jackson & Mullholland (1993; p805). Well 110/07b- 6 was clearly a test of the structure with the greatest amplitude, at the northern end of the profile. This slightly deviated well proved 450 m of (presumed) Namurian Bowland Shale Formation (unbottomed) beneath 550 m of Millstone Grit Group, Westphalian strata being absent beneath the Base-Permian unconformity (Fig. 3b). As noted above, northward-vergent structures have been identified on the northern edge of the Q109 Arch (Fig. 3a), and they have also been mapped beneath the northern part of the Deemster Platform. Several NNW-SSE to N-S trending graben of the EISB (Godred Croven, Gogarth and East Deemster basins) discordantly overlie this Carboniferous hinge-zone. The inversion belt is very similar in its structure and orientation to the Ribblesdale Fold Belt of the Lancashire onshore, representing the Variscan-inverted Bowland Basin (Corfield *et al.* 1996; Kirby *et al.* 2000). It seems logical to infer connection of the two, via the Fylde coast of Lancashire, as proposed by Corfield et al. (1996). If this inference is true, then the southern edge of the zone may represent a reactivated extensional fault, analogous to the Pendle Lineament of Lancashire; and the Visean carbonate platform (Holy Island and Conwy platforms) to the south, with a thin or absent Namurian cover, are the equivalent of the Central Lancashire High (Kirby *et al*. 2000).

That part of the Eubonia Tilt-block lying east of the Keys Fault was subsequently almost obliterated by the combined effects of latest Variscan inversion and pre-Permian erosion. The original eastern limit of the tilt-block is uncertain. It likely continued beyond the Tynwald Basin, where the *en-echelon* faults of the Lake District Boundary Fault System may have acted as transfer faults, offsetting extensional subsidence farther south into the Craven Basin. On the northern margin of the tilt-block, to NW of the Eubonia-Lagman Fault System, an extensive shallow marine carbonate platform developed in

Visean time. This is well represented by outcrop in the south of the Isle of Man (Chadwick *et al*. 2001), the northern edge of the Lake District and adjacent offshore (Ramsey-Whitehaven Ridge) (Fig. 2). Because of significant pre-Permian uplift and erosion, it is not possible to determine the subsidence regime in which Westphalian strata were deposited, but it was probably dominated by post-extensional thermal subsidence, as elsewhere in southern Britain, the depocentre lying near Manchester (Fraser *et al.* 1990; Fraser & Gawthorpe *et al.* 1990).

A few wells penetrate the Carboniferous sequence beneath the Peel Basin (Fig. 2) and demonstrate that an extensive carbonate platform (Manx Platform and Strangford Shelf) extends west to Ireland and north towards the North Channel. The present study revealed that the undifferentiated Carboniferous strata on BGS (1994) mapping are principally of Visean age, Namurian strata being largely eroded (Pharaoh *et al.* 2016a). The Permo-Triassic Peel Basin has the form of an asymmetrical graben controlled by a major bounding fault on the northern side (Fig. 4c), and extensional faults with smaller throws on the southern side, developed in the hangingwall of the Barrule Thrust (Chadwick *et al.* 2001). Lack of evidence for significant Carboniferous syndepositional throw, and the larger Permo-Triassic throws, suggests that there was probably not a significant basin here in Visean time, although the poor quality of the seismic data allows some uncertainty. Faulting at the top of the Appleby Group (Permian) has a predominantly NW-SE trend (Quirk *et al.* 1999), akin to that of the North Channel Basin.

In contrast, the Solway Basin, underlying the Permian-Mesozoic Carlisle Basin along strike to NE of the Peel Basin, is asymmetrical with a principal controlling fault on the southern side (Ramsey-Whitehaven Ridge) (Fig. 5a). The Carboniferous basin fill comprises fluviodeltaic Border and Yoredale Group strata with greater affinity to the Northumberland Trough sedimentary sequence than the carbonate platforms of the southern Irish Sea (Chadwick *et al.* 1995), together with a greater thickness of preserved Pennsylvanian strata.

The present study found no convincing evidence for the presence of Carboniferous strata beneath Permo-Trias in the Portpatrick Basin, the southern part of the North Channel Basin complex: the only well to penetrate Permian in this basin (111/15-1) unfortunately terminated in early Palaeozoic rocks having passed through the marginal fault. The absence of Carboniferous strata may be a consequence of erosion following late Variscan inversion on the NNW-trend (see below). However, they are present within re-entrants at the northern edge of the Southern Upland Massif (Stranraer, Strangford Lough), and are certainly present to north of the Southern Upland Fault (Larne, Rathlin basins and SW Arran Trough). All of these basins are very poorly explored by deep boreholes and only very general conclusions can be made about their Mississippian evolution, largely by inference from nearby analogues onshore (Read *et al*. 2002).

Early phase of Variscan inversion

Through Pennsylvanian 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 northward thrust and nappe emplacement occurred in southern Britain, S Wales and S Ireland, but the region lay in the northern foreland of the Variscan Foldbelt (Besly 1988; Ziegler 1990; Pharaoh *et al.* 2010). In late Pennsylvanian (Westphalian C) time, an early phase of inversion was followed by deposition of strata of the Warwickshire Group, above a regional unconformity (Eastwood *et al.* 1937; Akhurst *et al.* 1997; Jones *et al.* 2011; Dean *et al.* 2011; Waters *et al.* 2011). The Whitehaven Sandstone Formation (equivalent to the Warwickshire Group and of latest Westphalian to ?Stephanian age) has divergent palaeocurrents to the south in Cumbria, and to the north at Canonbie, reflecting penecontemporaneous growth of the Solway inversion anticline (Jones *et al.* 2011). In the EISB, this study has identified SSW-ENE trending inversion structures parallel to the Eubonia-Lagman Fault System in the north (Fig. 6), as well as in the Môn-Deemster inversion belt described above. The study has shown that the early phase of Variscan inversion structures are cut discordantly by the NNW-SSE to N-S trending faults of the Permian-Mesozoic main graben structures of the EISB, such as the Godred Croven Fault and the western marginal 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, prior to deposition of Warwickshire Group strata (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).

Later phase of Variscan inversion

In late Pennsylvanian time, the final deformation phases of the Variscan Orogeny are associated with the closure of the Uralian Ocean basin and collision of the Kazakhstan and Siberian plates (Zonenshain *et al.* 1984; Puchkov 1997; Brown *et al.* 2002), resulting in W-E oriented compressional stress (Coward 1993; 1995). In the study area, inversion occurred along NNW-SSE to N-S trending faults such as the Keys Fault, Gogarth Fault, the western marginal fault of the East Deemster Basin and the Formby Point Fault System. Evidence for this is provided by the Carboniferous subcrop pattern presented by BGS (1994). The Pre-Permian subcrop inset in the marginalia of this map clearly shows erosion of Westphalian strata in NNW- to N-S trending belts associated with the hangingwalls of the Keys Fault (Fig. 5b), Gogarth Fault (Fig. 4a) and Lake District marginal faults (Fig. 5c. By contrast, Westphalian strata are well preserved on the footwall of these structures. The seismic data indicate the presence of N-S trending anticlinal folds cored by Namurian strata, dissected by faulting on their overturned limbs. Similar subcrop patterns, with Namurian subcrops in the cores of Variscan inversion anticlines e.g.. the Murdoch Anticline, are observed in Quadrants 43 and 44 in the southern North Sea (Corfield *et al.* 1996), and indeed, the two basins exhibit a similar degree of inversion. At present the faults are extensional structures of Permian and younger age; but these are here inferred to have initiated as thrusts on the overturned limb of the anticlines during Variscan inversion, as reported in the Ogham Inlier by Quirk & Kimbell (1997). Seismic mapping of the subcrop in the present study confirms this pattern and has identified a possible interference structure between the two trends in the Ribble Estuary Inlier (Fig. 6). Although it is conceivable that inversion on faults with both WSW-ESE and NNW-SSE trends could have occurred in one Variscan phase of inversion, comparable to the partitioned deformation system advocated for the Northumberland Basin by De Paola *et al.* (2005), the above evidence would appear to suggest two phases of nearly orthogonal Variscan inversion are more likely. Extensional reactivation of the NNW- to N-S trending late Variscan inversion structures in W-E extension during Permian to Mesozoic time, facilitated development of NNW-SSE to N-S trending graben of the EISB, strongly discordant to the strong SW-NE structural grain established by Caledonian compression, Mississippian extension and early Variscan inversion. Strong uplift and erosion during the Variscan inversion led to complete removal of the Pennine Coal Measures strata underlying the Lagman Basin. The ancestral Keys Fault played a key role in partitioning the former Eubonia Tilt-block into western and eastern segments, the latter being almost obliterated by post-Variscan events. Inversion on the same trend may have led to uplift and erosion of Carboniferous strata deposited within basins on the North Channel Basin complex.

Post-Variscan structural evolution

The Post-Variscan structural evolution of the EISB has been thoroughly described in numerous previous publications (BGS 1994; Jackson *et al.* 1987' 1995' 1997; Jackson & Mulholland 1993). As a result, only a generalised account, focussing on those elements where the Palaeozoic structure has a bearing, will be presented here. Following the Variscan basin inversion and regional uplift described above, there is clear evidence on seismic profiles for the erosion of Pennine Coal Measures strata from the crests of inversion anticlines, and tectonic dissection of the latter adjacent to the Keys, Lagman, Lake District Boundary and Formby Point faults prior to deposition of Permian strata. Jackson & Mulholland (1993; p793) and Jackson *et al.* (1997; Figure 2) recognised significant thickening of the Appleby Group (Lower Permian), possibly to as much as 1150 m (Jackson & Mulholland 1993), in a belt extending from the Berw Basin to the Formby Oilfield. For example, the well 110/11-1 proved 763 m of Collyhurst Sandstone Formation

(Appleby Group), while 110/7-2 12 km to the north proved only 40 m, and none is present in the vicinity of the Morecambe fields. The belt of thick Appleby Group strata directly overlies the Môn - Deemster Foldbelt, providing strong evidence for significant early Permian penecontemporaneous relief within, and deep erosion of, the tectonically weakened inversion belt. The area must have had a substantial topography in early Permian time. It is interesting to note that significant pre-Permian palaeotopography was described at Formby by Falcon & Kent (1960).

A series of NNW-SSE to N-S trending rifts began to develop in response to W-E extension affecting the crust of the Pangaea Supercontinent that was established during the Variscan Orogeny (Whittaker 1985; Coward 1995; Chadwick & Evans 1995). In the Worcester and Knowle basins onshore, rifting was able to exploit the N-S ('Malvernoid') grain previously established by late Precambrian orogeny (Pharaoh 1987; Barclay *et al.* 1997) and subsequent Variscan inversion (Chadwick 1993). The rifts propagated with stepwise, *en-echelon* offsets through the province, from the Stafford and Cheshire basins and EISB through the Portpatrick and Larne basins and the North Channel to the western Scottish offshore basins (Ziegler 1990). The Solway and Peel basins subsided less than the EISB, and are elongated SW-NE, reflecting structural control by the extensionally-reactivated Caledonide 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). By Triassic time, the EISB was a mature component of the Central European Basin System (Scheck-Wenderoth *et al.* 2007; Pharaoh *et al.* 2010), receiving up to 5km fill of Sherwood Sandstone Group clastic sedimentary rocks and Mercia Mudstone Group mudstones and evaporites (Jackson & Mulholland 1993). Small relict outliers of Lias (early Jurassic) strata in the Carlisle Basin (Warrington *et al.* 1997), Peel Basin (Chadwick *et al.* 2001) and EISB (Jackson & Mulholland 1993) indicate that subsidence continued into Jurassic time. Evidence for mid- 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 & Mulholland 1993; Quirk *et al.* 1999). 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 (Pharaoh *et al.* 2016b).

Opening of the Atlantic Ocean east of Greenland by Paleocene times associated with putative Icelandic Plume activity (e.g. Brodie & White 1994; Nadin & Kuznir 1995) resulted in voluminous magmatism in the Inner Hebrides and in N Ireland just to the west of the study area. The Fleetwood Dyke Complex (Kirton & Donato 1985) was intruded *en echelon* across the main graben of the EISB. Magmatic and thermal processes on a lithospheric scale resulted in regional thermal doming of the crust below the EISB (White 1988) in Palaeogene or possibly, late Cretaceous, time (Cope 1994, 1997). Across the study area, the combination of enhanced regional and local heat flow led to a further phase of hydrocarbon generation (Cowan *et al.* 1997; Meadows *et al*. 1997). Superimposed on the regional, thermal uplift described above were the effects of later crustal shortening, associated with the developing Alpine Orogeny in southern Europe. Apatite fission-track data indicate a second Cenozoic phase of 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 southern North Sea (Van Hoorn 1987; Badley *et al.* 1989; Chadwick 1993). 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 southern side of the 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 e.g. the Rhyl and Lennox fields (Haig *et al*. 1997), reflecting the 'buttressing' effect of the margins of the EISB (Pharaoh *et al.* 2016b). Throughout the EISB, seismic data indicate the presence of gentle Cenozoic inversion anticlines (Figs. 4a, b, c) superimposed on an earlier generation of Variscan inversion anticlines (Pharaoh *et al.* 2016a; b), the 'posthumous' tectonic style recognised by Jackson & Mulholland (1993). Further tightening of the Variscan inversion anticlines during Cenozoic (Alpine) crustal compression resulted in the development of more open structures in the Permo-Triassic cover. This was likely an important process in the generation of the traps in the Hamilton fields (posthumous upon the Môn-Deemster inversion belt) and the Millom, Dalton and Calder fields (posthumous on the Keys-trend of latest Variscan inversion).

Petroleum systems of the Carboniferous basins of the EISB

In the EISB, a proven petroleum system is present, involving a Carboniferous source (Colter & Barr 1975; Cowan 1991; Stuart 1993; Armstrong *et al.* 1997), reservoirs of the Ormskirk Sandstone, locally the uppermost formation of the Triassic Sherwood Sandstone Group, and halite seals (Fig. 7). A substantial number of exploration wells have been drilled, but few penetrate the Permian and the potential pre-Permian resource underlying the EISB fields is poorly known. The North and South Morecambe gasfields (Fig. 6), with a combined in place recoverable of 5.2 tcf (Cowan 1996), were discovered in the 1970s and lie in large regional anticlines associated with rollover and salt-facilitated low angle detachment faulting, of Triassic to Jurassic age (Knipe *et al.* 1993). Further modification of trap geometry occurred in Miocene time as a result of Alpine inversion. An initial charge of hydrocarbons (probably mostly oil) in Jurassic time was originally thought to have been derived from Pennine Coal Measures source rocks, as in the southern North Sea (Bushell 1986). Subsequently the Bowland Shale Formation was confirmed as the source (Armstrong *et al.* 1997). This early charge was associated with the formation (at about 180 Ma) of a 'platy-illite' layer, interpreted as a palaeo-hydrocarbon-water contact (Bushell 1986; Woodward & Curtis 1987; Knipe *et al*. 1993), which was lost during the early Cretaceous and the present (mostly) gas charge is believed to result from a further cycle of hydrocarbon generation (also from the Bowland Shale Formation?) associated with an elevated geothermal gradient during the early Cenozoic (Cowan & Bradney 1997). Hydrocarbon migration continues in the basin to the present day, as witnessed by the seepage of oil into Quaternary sands and peats at Formby, on the Lancashire coast.

In the 1990s, the Hamilton, Douglas, and Lennox fields, with a mixture of oil and gas, were discovered parallel with the North Wales coast in the southern part of the EISB (Fig. 6). Most of the deep wells of these fields encountered Millstone Grit Group below the Variscan Unconformity, as at Formby. 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 (correlative of the Bowland Shale Formation) of NE Wales thereby proving the Bowland Shale source (Armstrong *et al.* 1997). 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 in North Wales (Falcon & Kent, 1960) . Waxy crude shows in the Millstone Grit Group in well 110/07b-6 (1510 m-1675 m; Released Geochemical Report) showed an isotopically similar source to shows in wells 110/07-2, 110/08-3 and Formby. The API of the Irish Sea oils range from 40-45 at Lennox and Douglas (Hardman *et al.* 1993) , to 37 at Formby (Armstrong *et al.* 1997), perhaps suggesting a less mature source in the onshore field. Many additional small fields have been discovered subsequently, mostly in the centre of the EISB and mostly containing gas, culminating with the Rhyl discovery in 2009. In the Irish Sea, no significant Carboniferous reservoirs or good shows have been reported but there is at least one discovery (113/27-2) in the Collyhurst Sandstone (Appleby Group).

Stratigraphy of the petroleum system

Carboniferous source rocks are shown in Fig. 7, as covering the lower part of the Namurian and highest part of the Visean where shales are developed; Pennine Coal Measures may make a contribution where preserved. The lithostratigraphical terminology used here is that introduced by Waters et al. (2011) to better integrate the offshore with the onshore geology than previous schemes (e.g. Jackson *et al.* 1999). 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 groups. Above the Variscan Unconformity the Permian Appleby and Cumbrian Coast groups, and the lower, tight part of the Triassic Sherwood Sandstone Group, also intervene. A Pendleian time slice (Fig. 9) highlights the persistence of the relatively deep marine hemipelagic successions (Bowland Shale Formation) across the central part of the British Isles, including the Craven Basin, EISB and westward towards the Dublin Basin (Ramsbottom *et al.* 1969; Cope *et al.* 1992; Jackson & Mulholland 1993; Wakefield et al. 2016). 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 characterised by a thick pro-deltaic ramp turbidites, overlain by a siltstone-dominated slope succession, in turn overlain by a fluvio-deltaic, delta-top sandstone (Collinson 1988; Wakefield *et al.* 2016). The hemi-pelagic successions have gamma values which suggest potential as source rocks. The overlying successions of the Pennine Coal Measures and Millstone Grit groups have potential as a combined 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 and 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 (Fig. 6). Interpretation of well logs and associated core analyses (biostratigraphy, poroperm etc) frequently provide alternative stratigraphic interpretations to those shown on the well composite log, and have been carried out in this study (Fig. 9a, b). Many authors have referred to the problems in identification that results from 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 EISB. 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 (Fig. 9b). This is important because it shows the probable topography of the Carboniferous surface, deformed and uplifted by the Variscan Orogeny, and the extent of erosion and eventual burial. The Cumbrian Coast Group comprises a varied sequence of thin sandstones, anhydrites, limestones, halites and mudstones, mostly red in colour. Underlying redbeds have therefore been interpreted either as a mudstone facies of the Appleby or as Warwickshire Group strata, on well composite logs. The favoured interpretation, combining all the seismic and well evidence, is that the red beds directly underlying the Cumbian Coast Group 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.

Source rocks

One of the key risks in the Palaeozoic of the greater Irish Sea province is the quality, extent and maturity of source rock intervals. Potential source rocks include coals of the Pennine Coal Measures (Westphalian) and upper Millstone Grit (Namurian) groups; shales of the Bowland Shale Formation and Millstone Grit Group (Pendleian and Arnsbergian); and older Visean shales (unproven by sample data), for example in the lower part of the Yoredale Group. Compilation of the Rock-Eval source rock geochemical data from released legacy reports revealed a small data set (264 samples), limiting the analysis which could be undertaken (Vane *et al.* 2016). Where penetrated, the Pennine Lower Coal Measures Formation, Millstone Grit Group and Bowland Shale Formation are mainly gas-prone strata with poor-fair remaining generative potential, and are mature to the gas window at the sampled intervals in Quadrants 110 and 113 (Vane *et al.* 2016). Some shales within the Millstone Grit Group have TOC values (Fig. 11f) and S1 hydrocarbon values (Fig. 11a) greater than the Bowland Shale Formation. 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 to fair. 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 Total Organic Carbon (TOC) and low residual hydrocarbon generative potential. Data is generally lacking to characterise kerogen types using a Van Krevelen plot, however data from well 110/02b-10 (Fig. 11b) suggests a kerogen mix between Type II and III for the Millstone Grit Group and Pennine Coal Measures. A similar mixed system can also be expected for the Bowland Shale Formation but with a higher proportion of Type II kerogens. The high TOC and widespread extent of the Bowland Shale Formation favour it as the primary source rock, at least in the southern part of the Irish Sea. The other potential sources are ranked as secondary to this.

Hydrocarbon maturation and generation

Vitrinite reflectance data (Fig. 11d) shows that the Bowland Shale source rocks in wells are mature for oil and gas generation (Corcoran & Clayton 1999; Vane *et al.* 2016). EISB oils were considered to have been derived from the source in the range 0.75-0.85% Ro maturity, and the condensate from >1.0% Ro (Armstrong *et al.* 1997). Given the structural complexity for the area of interest, a singular burial trend and maturity profile cannot be defined. Cowan *et al.* (1999) gave examples of varying thermal and burial history at the basin margins changing over tens of kilometres. Three wells show a correlation of maturity increase with depth within the T_{max} dataset: 110/07b-6, 110/02b-10 and to a lesser extent 113/27-1, indicating 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 or possibly due to T_{max} suppression caused by variable kerogen and free oil composition (Fig. 11c). Onshore Isle of Man boreholes (Shellag, Ballavarkish, Black Marble Quarry; Fig, 5) show a similar range of T_{max}, albeit with few samples (Racey 1999).

Basin modelling

A lack of preserved post-Jurassic strata has resulted in a range of burial and thermal models for the EISB, for example Cenozoic uplift estimates ranging from <1 km to up to 3 km (Cowan *et al.* 1999; Quirk *et al.* 1999 and references therein). In this study, well 110/07b-6 was chosen for burial and thermal modelling as it had the most complete geochemical profile and thick Carboniferous section (Gent 2016; Fig. 12). The well is situated on a minor Variscan structural high, and is considered reasonably representative of the more marginal areas of the basin. The burial model was matched to the measured vitrinite reflectance (VR) profile and the calculated VR profile (from T_{max}) (Fig. 12). Using published studies (Cowan *et al*. 1999; Quirk *et al.* 1999) and seismo-tectonic interpretations from this study a 700 m uplift event in the late Carboniferous, followed by a minor 150 m uplift during development of the Late Cimmerian Unconformity, and a final 1100 m uplift and increase in palaeo-heatflow in the Cenozoic were included. The modelling shows that burial of the Bowland Shale Formation source rock in the Carboniferous resulted in the early-mid mature oil window being reached, before uplift and subsequent deeper burial in the early Cenozoic, just reaching main gas generation in the base of the drilled strata (Fig. 12). This is consistent with the oil shows documented in the well geochemical report (Geochem Laboratories Ltd 1988). Carboniferous trap formation, migration and generation were all likely to have occurred during the Variscan Orogeny. However, subsequent uplift would have almost certainly breached the traps. Migration and trap formation was renewed in the Mesozoic and Cenozoic, with any modern day hydrocarbon accumulations required to have survived the potential structural breach as a result of Cenozoic inversion.

Migration

Migration of hydrocarbons into Triassic reservoirs and traps has clearly been successful as evidenced by the producing oil and gas fields of the EISB. Oil migration to the Triassic Hamilton fields may have occurred, vertically along faults, in Jurassic and Cretaceous times (Yaliz 1998; Haig *et al.* 1997; Yaliz & Taylor 2003). This study has highlighted how these fields overlie the Môn-Deemster inversion belt described above (Fig. 6), the structures of which may have acted as first stage reservoirs, subsequently breached to allow migration into overlying Triassic traps, formed posthumously as late as Cenozoic time, on a template created by the Variscan inversion structures. In a similar way, the Millom, Dalton and Calder fields, lying close to the Keys Fault, and Lennox Field, close to the Formby Point Fault, are Cenozoic age traps formed posthumously on a template provided by the second phase of Variscan inversion structures. 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 within the dismembered Eubonia Tilt-block 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 a conceptual Carboniferous petroleum system model, 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. In the north the boundary is strongly faulted (Lagman, Eubonia and Lake District boundary faults).

Characteristics of potential reservoirs

A reservoir evaluation of Permian and Carboniferous intervals, designed as a quick-look regional overview, was based on legacy core plug-measured porosity and permeability data and continuous petrophysical interpretations for 8 wells (Hannis 2016). Net-to-gross, porosity and basic permeability estimates were calculated for each formation, summarised in Table 1. In general, the results illustrate fairly low net to gross values of less than 10% (except in the Permian-aged Appleby Group where net-to-gross was 79%), porosities (highest formation averages mostly around 10% but up to 19 % in the Appleby Group) and mainly poor average permeabilities (highest formation averages mostly less than 10 mD). Further examination of the distribution of potentially higher permeabilities within the Millstone Grit sandstone intervals could be worthwhile (Table 1). The core plug measured porosity versus permeability data by formation is exhibited in Fig. 13.

The aeolian-dominated Permian Appleby Group strata that include the Collyhurst Sandstone are a prospective reservoir interval. The group as proven in well data 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). Based on 6 wells in Quadrant 110 in the depth range 1300-2400 m, maximum measured core porosity is 21% with a highest formation average in all wells of 13%. Permeability is however poor, with a maximum measured permeability of 71.5 mD (vertical (k_v)), and a highest formation average of 0.8 mD (horizontally,k_h) and 7.90 mD (vertically). Petrophysical analysis has confirmed the group as being a sandstone-dominated interval with an average net-to-gross ratio of 79%. Petrophysical 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 (Table 1 and Hannis 2016).

The Warwickshire Group is the equivalent of the Ketch and Boulton formations of the southern North Sea in Quadrant 53 and Quadrants 43-44 (Waters *et al.* 2011). Onshore, the Warwickshire Group of North Wales and Cheshire Basin comprises predominantly red, brown, purple-grey mudstones and sandstones and locally green-grey siltstones and mudstones with thin coals. However, potential reservoir sandstones can be locally significant. The amount of sandstone relative to mudstone and siltstones within constituent formations of the Warwickshire Group varies considerably. In West Cumbria, 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). The Halesowen Formation was productive in the small mined Coalport Tar Tunnel ‘field’ in Shropshire during the 18th and early 19th century (Smith *et al.* 2005). In the East Midlands, the Warwickshire Group group has been documented to have better reservoir characteristics than productive older late Carboniferous strata, but was spatially confined to the synclines (BGS 1984; Pharaoh *et al.* 2011). 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. Therefore investigation of the Warwickshire Group as a reservoir interval offshore was considered, though seismic mapping indicated a limited extent in the greater Irish Sea province (Fig. 6) and there are no well penetrations and therefore no reservoir data for the group. However, Bolsovian-Asturian (Westphalian C-D) age strata are recorded in well 33/22-1 along strike in the Kish Bank Basin (Jenner 1981).

In the EISB, the Pennine Coal Measures Group comprises interbedded grey mudstone, siltstone and pale grey sandstone, commonly with mudstones containing marine fossils in the lower part of the lower and upper part of the middle subdivisions, and more numerous and thicker coal seams in the intervening interval. The group shows an overall blocky to erratic log response, with thick high gamma mudstone and siltstone intervals and relatively thin (3-15 m) low gamma sandstones. The sandstones show considerable variation in wireline log character, including 'boxcar' motifs in thick, distributary channel sandstones (Wakefield *et al.* 2016). Onshore, sandstones are also 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). Based on five wells in Quadrants 110 and 113, in the depth range 1400-3050 m, maximum measured core porosity is 10% with a highest formation average in all wells of 6%. Permeability is generally poor with a maximum measured horizontal permeability of 9.43 mD (k_h), and a highest formation average for k_h of 1.07 mD. Petrophysical analysis of the Pennine Coal Measures Group provides a similar outlook, with an average net to gross of 9%. Net intervals have reasonable porosities, with the highest average porosity at 11%. Permeability is generally poor with the highest average permeability estimated at 0.8 mD. However, permeability up to 61 mD was estimated in one well (110/02b-9; Table 1, Hannis 2016).

The Namurian-aged Millstone Grit Group comprises cyclic sequences of quartzo-feldspathic sandstone, grey mudstone, thin coal and prominent seatearths, resulting from deposition by repeated progradational deltas (Collinson 1988). Common marine bands are present and represent discrete flooding events (Waters & Condon 2012). 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 50m thick) occupy incised valleys (Waters & Condon 2012; Wakefield *et al.* 2016). Jackson *et al.* (1997; Figure 6) identified a Kinderscoutian sandstone unit up to 90 m thick in the Liverpool Bay region (111/20-1), which can be correlated with wells farther north (112/30-1 and 113/27-2) although considerably reduced in thickness. Onshore, Millstone Grit sandstones are encountered in NE Wales (e.g. Cefn-y-Fedw, Gwespyr Sandstone, Aqueduct Grit), 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 to SW under the Cheshire Basin (Collinson *et al.* 1977; Smith *et al.* 1995). This pattern continues into the offshore of the EISB with Namurian absent at the Rhuddlan well on the North Wales coast (Figs. 5, 9b). Based on samples from four wells in Quadrants 110 and 113, at 1950-3550 m depth, maximum measured core porosity is 10 % with a highest formation average in all wells of 6% (Table 1). Permeability is poor, the maximum measured was 0.37 mD (k_h), and the highest formation averages for k_h and k_v were 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 10 %. Net intervals have a reasonable porosity, the highest average porosity is 11 %. Permeability is poor with an average estimate of 0.2-2.1 mD, apart from one well 113/27-2, which shows an average of 367.7 mD (Table 1). Further analysis of these sandstones could therefore be beneficial (Hannis 2016).

The Bowland Shale Formation is only examined in the wells 110/11-1 and 110/07b-6, 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 may be present. Well 110/07b-6 encounters a total of 16 m of these sandstones, giving a net-to-gross of 3%. (The other well examined, 113/27-2, contained no net intervals). No core samples were taken, but petrophysical interpretation revealed that the net intervals had porosities up to 23%, although the average porosity was 7

%. Permeability estimates appear poor with an average of 0.7 mD and maximum of 16.2 mD (Table 1, Hannis 2016).

Carboniferous Limestone Supergroup sequences are interpreted to be widespread over the EISB and thus worthy of investigation as a reservoir. Petrophysical analysis of the limestones encountered in two wells (112/25a-1 and 111/25A-1) appear clean, but have too low matrix porosities (less than 5 %) to be considered as a reservoir (Table 1), but accumulations could be hosted in secondary porosity as a result of karstfication or fracturing. Onshore, the Hardstoft Oilfield in Derbyshire (Craig *et al.* 2013) 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 & Kent 1960). Karstified limestones such as those known from Anglesey (Walkden & Davies 1983) and apron reefs like those which crop out at Castleton, Derbyshire might be present in the offshore. Seismic evidence for the possible presence of reefs towards the top of the ramp of the Eubonia Tilt-block in Quadrant 109 (Fig. 4a) was described above and indicated schematically in Fig. 4a. Waulsortian mud-mounds 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 in the Craven Basin. In the prolific Williston Basin of Canada, collapsed mud-mounds up to 100 m tall provide excellent porosity but were initially hard to identify on seismic data (Kupecz *et al.* 1996).

Seal rocks

The Cumbrian Coast Group, which includes the Manchester Marls (Fig. 7), provides the most extensive potential seal to Permian or Carboniferous rocks across the whole of the greater Irish Sea area. The unit consists of thick evaporites in the north and central East Irish Sea, thinning southward, passing laterally into dolomitic mudstones (Jackson & Mulholland 1993; Wakefield *et al.* 2016), and is encountered in wells in surrounding sub-basins. This seal has been proven to trap hydrocarbons in the well 113/27-2, and sealing potential is proven in 112/25a-1, with minor gas shows in the tight Appleby Group. In the producing EISB fields, any Cumbrian Coast Group seals were breached as 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), various fields in the Silver Pit and Cleaver Bank basins of the southern North Sea and numerous fields in the Netherlands and Germany (Pletsch *et al.* 2010), and could be expected to work in Carboniferous basins of the Irish Sea.

Hydrocarbon prospectivity of the Carboniferous basins outside the EISB

Whilst basins of the greater Irish Sea province outside the EISB have extensive seismic coverage of variable quality, there are few wells. Data is therefore lacking to constrain their hydrocarbon systems and is heavily dependent on onshore analogues.

Solway Basin

The Permian – Jurassic Solway Basin, linked NE to the Carlisle Basin and SW to the Peel Basin is underlain by a Carboniferous basin of the same trend, an extension of the Northumberland Trough (Chadwick *et al.* 1995; Fig. 2). 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 (Fig. 7). The Yoredale Group sandstones, limestones and siltstones represent a fluviodeltaic depositional environment (see Wakefield *et al.* 2016) which is a northward lateral equivalent of the basinal Bowland Shale Formation, i.e. the Bowland Shale facies is not proven and may not be present. The presence of delta-top lacustrine facies is a possibility, but has not been demonstrated. In the onshore Cumberland Coalfield, the coals are gassy (Colter 1997), but the Pennine Coal Measures Group have not been penetrated offshore in the Solway Basin. Potential Carboniferous reservoir intervals include a relatively small area of Warwickshire Group on both sides of the Maryport Fault (Figs. 5a, 6) and the Fell Sandstone Formation in the main part of the basin.

Peel Basin

The Peel Basin is a Permian-Jurassic basin lying between the Isle of Man and Northern Ireland, underlain by a Carboniferous carbonate platform. Wells 111/25a-1 and 111/15-1 penetrated the Mississippian age Carboniferous Limestone Supergroup, in contrast to the time-equivalent 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 being present in younger strata between 111/25a-1 and the Isle of Man coast, but there is no data to test this hypothesis. The seismic reflection data are generally of poor quality, but allow the presence of a small outlier of Namurian strata to NW of the Isle of Man. The Peel Basin may extend to the Carlingford Lough area near the Irish border, south of the Mourne Mountains (Fig. 2). BGS boreholes (in Quadrant 112, near the Irish coast) 73/65 and 73/67 are of probable Visean age and form a rim to the Lower Palaeozoic Longford-Down Massif. BGS borehole 71/43 near the Isle of Man coast was dated as Namurian. The data available preclude evidence of a working Palaeozoic petroleum system in the Peel Basin, a conclusion previously reached by both Newman (1999) and Quirk *et al*. (1999).

North Channel Basin

The North Channel Basin is a NW-trending Permo-Triassic basin complex lying between the Southern Uplands and the Longford-Down Massif of N Ireland (Quinn 2008) and forms the main rift through the massif. Two tilt-blocks, the E-dipping Portpatrick and W-dipping Larne sub-basins, recognised by Maddox *et al.* (1997), are separated by the Southern Upland Fault (Fig. 2). Several smaller basins lie parallel in Scotland (Stranraer, Lochmaben) and Ireland (Strangford Lough). In the Portpatrick Sub-basin, the underlying strata are possibly Devonian, although the seismic is poorly resolved because the only well (111/15-1) passed through a fault adjacent to the Southern Uplands, and did not prove a Carboniferous section. Data is lacking for the presence of source, reservoir and seal in this area (Maddox *et al.* 1997). Permo-Triassic and underlying Devonian and Carboniferous strata are present onshore in the Larne and Lough Neagh basins of N Ireland. Onshore in the Midland Valley of Scotland and in N 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; Read *et al.* 2002; Underhill *et al.* 2008; Reay 2004; 2012). Onshore in N Ireland, a Carboniferous prospect was drilled by Infrastrata plc in Woodburn Forest in 2016, without success (website). Seismic interpretation offshore (Pharaoh *et al.* 2016a) has included a Carboniferous succession in the Larne Basin buried to 5000 m and with faulting and folding observed offering potential for structural traps. However the interpretation is poorly constrained by data, precluding detailed assessment of petroleum system elements.

Brief mention can be made of the Rathlin Trough, which lies outside the study area, and for which only limited seismic data, covering the offshore extension of the Machrihanish Coalfield, have been studied. The source rocks include coals and oil shales (Murlough Bay Formation) of early 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 (Read *et al.* 2002). Drilling took place at Magilligan in the west of the basin and at Ballinlea in 2008. In the latter well, oil was produced from the Carrickmore Formation sandstones (Providence 2013) of the wide Visean subcrop (Smith 1985).

Petroleum system knowns and risks

The distribution of the principal Carboniferous source rock (Bowland Shale Formation) as inferred from the seismic interpretation is constrained by a few borehole penetrations in the EISB, 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 time-equivalent Yoredale facies is therefore poorly known. The lack of any offshore well data requires analogy with the adjacent onshore Carboniferous 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 beneath the Peel Basin. Attenuation of the Carboniferous sequence southwards towards the Welsh Massif (Fig. 4b, 9a) 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. Similarly, the reservoir porosity-permeability characteristics are poorly known over large parts of the region studied. The petrophysical analyses presented here suggest that the Carboniferous sandstones beneath the Morecambe fields have very poor porosity and permeability, confirming information provided by Centrica (*pers. comm.* 2015). This is no doubt a consequence of their deep burial, and processes such as platy-illite development and silica cementation which severely affect even the overlying Triassic formations (Colter 1989; Bushell 1986; Woodward & Curtis 1987; Cowan 1991; Stuart 1993). Extensive carbonate platforms surrounding the Isle of Man (Manx Platform) and off North Wales (Colwyn Platform) also have unknown poroperm characteristics. Until more is known about possible secondary porosity (following dedolomitisation) and fracture density, the reservoir properties of these areas are ranked as high risk.

The Mercia Mudstone Group is a proven caprock to Sherwood reservoirs and is present throughout the EISB but is absent across the margins of the basin complex. The potential seal of the Permian Cumbrian Coast Group sequence thins and fails in the same directions. In the EISB a relatively thick shale and evaporite (St Bees Evaporites, Cumbrian Coast Group) may be developed. The same is true in the Portpatrick and Larne basins, where several Triassic halites are present (Quirk *et al.* 1999; Quinn 2008).

Analysis of seismic data, integrated with well, core data etc, indicates that the marginal areas of the EISB hold the greatest potential for undiscovered hydrocarbon resources in the Carboniferous, although the geochemical, petrophysical and other essential data are scant. In general, the presence of an effective seal is considered to represent the biggest risk in the hydrocarbon system at the margins of the EISB. Yet-to-find prospects are anticipated to be relatively small in volume and with shallow column heights supported by Carboniferous intra-formational seals. The most prospective parts of the region, outside the Triassic play, are considered to be:

- Thick Westphalian combined reservoir and source rock sequences preserved in the Eubonia Tilt-block in Quadrant 109 (Fig. 4a), located outside the main Permian-Mesozoic graben system and less affected 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 (the Môn-Deemster Foldbelt; Fig. 4b) correlated with structures on the Formby Platform, and the onshore Ribbledale Foldbelt, from which hydrocarbons sourced by a thick Bowland Shale sequence have leaked into the overlying, Triassic-hosted Hamilton fields (block 110/13). The biggest risk here is whether reservoirs exist and remain unbreached at the pre-Permian level, and retain good poro-perm 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 (Fig. 4a), in Asbian reefal facies with enhanced secondary porosity. Here, source rock presence and migration pathways, reservoir properties and seal quality are major risks.

- The Ribble Estuary Inlier east of the Formby Point Fault (Figs.5c,6) may contain a working petroleum play. It lies adjacent to the deep Deemster Basin where there is a thick sequence of Upper Carboniferous sedimentary rocks preserved, and between the Formby and Lennox fields.

Well 110/9-1, within the Deemster Basin was dry, but appears to have good porosity in the Ormskirk Sandstone though no shows. Fluorescence was recorded in the Appleby Group.

- A potential play exists sourced from the Bowland Shale Formation in the deep Godred Croven Basin drilled by 110/11-1emigrated into the Carboniferous reservoir 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.

Discussion

The pre-Permian structural synthesis presented here is speculative in view of the limited number of offshore well penetrations of Carboniferous strata. For example, further tectonic partitions may exist within the inferred Eubonia Tilt-block. It is possible, for example, that the eastern part of the structure (underlying the Keys and Tynwald basins of the EISB) may represent a separate tilt-block with a hinge in the Lake District Boundary Fault System, and a master controlling fault in the west (ancestral Keys system). The presence of such a basin, referred to as the Lancaster Fells Basin, was inferred by Cowan *et al.* (1999). However, the available evidence suggests that the NNW structural trend did not play a significant role until latest Carboniferous time, so that an ancestral Keys Fault is regarded an unlikely Visean structural element. The nature of the link between the structures of Quadrant 109 and onshore Lancashire has been much speculated on in the past (e.g. Ramsbottom *et al.* 1978). Jackson & Mulholland (1993) recognised the Menai Strait-Pendle Line link, but preferred to link the Q109 Arch to the High Haume Anticline of the Furness Inlier, in the southern Lake District. This paper shows that the Ribblesdale Foldbelt does extend west of the Leyland Basin and Formby Point Fault (c.f. Jackson & Mulholland 1993; Figure 4 and p797) and links to the Q109 Arch, via the Môn-Deemster Foldbelt. More detailed seismic mapping of the Upper Carboniferous interval will be required to elucidate what is probably an intricately folded subcrop pattern here. We support the proposed continuity of the Bowland Basin southwestwards into the offshore area, as inferred by Corfield *et al*. (1996) and Cowan *et al*. (1999). From the perspective of hydrocarbon prospectivity, the presence of the prolific Bowland Shale Formation source rock interpreted across much of the EISB has been a key element in the hydrocarbon system of the overlying Permian to Mesozoic basins. Prospective reservoir intervals with moderate porosity are likely to exist in the Warwickshire Group and Pennine Coal Measures Group in the marginal parts of the EISB, although the permeability is likely to be poor. The EISB lay to west of the main Pennine deltaic and fluviatile fairway in the onshore (Fraser *et al.* 1990), and consequently shows a lower net/gross sand ratio.

In a review of the deep reflection seismic data for the Irish Sea, principally BIRPS' WINCH lines and some deep data from JEBCO, England & Soper (1997) state that from this limited dataset, there is no clear evidence for reactivation of earlier structures during either Carboniferous sedimentation or Variscan inversion. Using the shallow seismic reflection data, this study describesthe presence of fold-thrust structures in the pre-Carboniferous basement and, in the Môn-Deemster Foldbelt, demonstrates their role in controlling both Carboniferous extensional and inversion structures. The interpretation presented supports the view of England & Soper (op. cit.) that the faults controlling Permian and Mesozoic basin development are discordant to the Caledonian, Acadian and early Carboniferous structural grain (as exemplified by the Q109 structures), and are therefore juvenile structures developed in late Westphalian to early Stephanian time. Evidence presented here suggests that these were initiated as a result of a late phase of Variscan inversion, reflecting W-E Uralide compression, superimposed on an earlier phase produced by N-S compression. The timing of these two inversion phases is imprecisely defined in the Irish Sea due to the significant missing stratigraphic section. However, in late Variscide intramontane basins in central France, N-S compression in Stephanian B time is followed by phases of compression on NW-SE (late Stephanian B) and W-E (mid-Stephanian C) principal stress axes (Gélard *et al.* 1986), the 'Bourbonnaise Phase' of Grolier (1971 Although interpreted in terms of systematic rotation of the principal horizontal compressive stress axis Gélard *et al.* 1986; Blès *et al.* 1989; Ziegler 1990), Faure (1995) considered these deformations a consequence of late Variscan orogenic collapse. In the UK region, other manifestations of the late W-E compressive phase may include the W-E oriented basaltic dykes, and a component of growth of N-S trending folds, within the Midland Valley of Scotland (Monaghan & Pringle 2004; Timmerman 2004), and W-E directed transport of fold nappes on the eastern margin of the Worcester Graben (Peace & Besly, 1997).

The observed variation in Variscan structural orientation in the Variscan Foreland of Britain is currently explained in terms either of one resolved compressional vector (Corfield *et al.* 1996), or of strain-partitioning across a heterogeneous basement template (e.g. De Paola *et al.* 2005). In the Irish Sea, it is difficult to argue for a strong control by a N-S oriented basement grain, as identified, for example, within the Midlands Microcraton (Corfield *et al.* 1996), and the presence of two discrete late Variscan deformation phases is regarded as a more likely scenario. Another expression of the multiple inversion history, and very significant for the formation of Ormskirk traps in the cover, is the impact of posthumous folding. This process, first recognised and described by Suess (1904), is very clearly demonstrated in the Irish Sea, where a template of Variscan inversion anticlines in the Carboniferous sequence underlies structures with similar trend but lower amplitude in the Permo-Triassic cover.

Conclusions

The study has demonstrated that the basins of the Irish Sea preserve a Phanerozoic geological history as complex as that of the UK onshore. A strong SW-NE structural grain was imprinted on the crust during late Precambrian and Caledonian accretion and orogenic deformation. Dipping zones of strong reflectivity in seismic sections are interpreted as major thrusts and shear zones, some of which can be correlated with known examples onshore. Mississippian rifting on SW-NE trending faults resulted in depocentres which accumulated marine shale source rocks, preceding regional thermal subsidence. The Eubonia Tilt-block is a major Carboniferous syndepositional element beneath the northern part of the EISB, but was partially dismembered by the formation of the ancestral Keys Fault system. The Eubonia-Lagman fault system formed the syndepositional bounding fault to the tilt-block. The Bowland Shale Formation forms the main source rock interval, with inferred thickest development likely just to north of the Môn-Deemster Foldbelt, the offshore correlative of the Bowland Basin, and its inversion, the Ribblesdale Foldbelt. This source rock is buried to depths >7 km under the Lagman and Keys basins and is probably post-mature there at the present day.

The Millstone Grit Group and Bowland Shale Formation contain thin clean sandstones locally up to 90 m thick which could be considered potential reservoirs. Prospective areas at these stratigraphic levels may exist at depth adjacent to the Keys Basin, and west of the Keys Fault. The Millstone Grit Group also has the potential to act as a secondary source rock, as do the Pennine Coal Measures Group when buried deep enough to achieve maturity. However, the latter were stripped from a large area of the EISB following Variscan inversion. Pennsylvanian strata exhibit marked thinning to the south onto the Conwy Platform. Burial by Upper Carboniferous sediments likely resulted in early maturation of kerogen in source rocks within the deepest basins, but destruction of reservoir porosity and permeability in the depocentres. Warwickshire Group sedimentary rocks were not so deeply buried, and are likely to retain better reservoir characteristics.

The Variscan Orogeny, in late Carboniferous time, caused uplift, folding and thrusting on both WSW-ENE (Môn-Deemster) and NNW-SSE to N-S (Keys-Gogarth) trends, probably in two phases, corresponding to well-documented main compressional phases of the Variscan-Uralian Orogen. The later inversion phase occurred on NNW-SSE to N-S trending zones of deformation which would subsequently become localised as the main synsedimentary bounding faults of the EISB in Permian to Mesozoic time. Corfield et al. (1996) provided a definition of inversion intensity. In the greater Irish Sea region, the intensity ranges from moderate (in the EISB, Solway and Clyde basins) to strong, with almost complete removal of the post-rift fill (in the North Channel basins and Peel Basin). The timing of these events is poorly constrained in the Irish Sea due to significant missing stratigraphic section, but by comparison with intramontane basins in France, is likely of intra-Stephanian age. The Variscan inversion structures have not yet been adequately tested as targets. They form both first-stage hydrocarbon reservoirs and the structural template for more gentle, 'posthumous' folds produced by Alpine inversion which form traps in the Triassic cover (e.g. the Hamilton fields). Deposition of Permian Appleby Group and Cumbrian Coast Group strata resulted in a potential reservoir - seal combination overlying the Carboniferous source rocks. Permian to Mesozoic rifting is along NNW-SSE and N-S trends. These faults cut discordantly across the early Carboniferous structures and have allowed late Cretaceous to early Cenozoic vertical migration of Carboniferous-sourced hydrocarbons into Triassic reservoirs. There is a migration route to Triassic reservoirs in the centre of the EISB because the Warwickshire Group and Appleby Group strata have been removed from that area, and the thin Cumbrian Coast Group seal breached, where the producing hydrocarbon fields are located. The Clyde-North Channel basin complex, Solway and Peel basins also contain Devonian and/or Carboniferous rocks beneath Permo-Triassic strata, but have likely been buried less deeply than those in the EISB. The North Channel basins may also have suffered significant Variscan inversion. Extensive 2D seismic datasets cover the latter areas but there are only four well penetrations. There have been no discoveries, interpreted to be largely a consequence of the absence of a regional seal comparable in quality to the Mercia Mudstone Group in the EISB. The prolific Bowland Shale source is also absent in these basins, being replaced by fluvio-deltaic sedimentation of the Yoredale Group. Very limited well penetrations do not presently allow a realistic assessment of the prospectivity of the Carboniferous strata underlying these poorly drilled basins.

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Figure captions

Fig. 1. Key data evaluated during the study (2D seismic, black; 3D seismic outline, grey; wells proving Carboniferous strata, black dot; wells used in the petrophysical study, black square).

Fig. 2. Key Mississippian structural elements of the greater Irish Sea province. Incorporates information from Maddox *et al.* (1997), Parnell (1997) and Shelton (1997). Location of Permo-Triassic basinal features (for reference purposes) in red: BB, Berw Basin; CP, Conwy Platform; DP, Deemster Platform; EB, Eubonia Basin; ED, East Deemster Basin; GB, Gogarth Basin; GC, Godred Croven Basin; KB, Keys Basin; LB, Lagman Basin; MF, Manx-Furness Ridge; NC, North Channel Basin; OP, Ogham Platform; PB, Peel Basin; Q109S, Quadrant 109 Syncline; SB, Solway Basin; TB, Tynwald Basin; WD, West Deemster Basin..The basin names used are those of the Permo-Triassic EISB and contemporary basins, following Jackson & Mulholland (1993) and BGS (1994), rather than those of the Carboniferous elements newly named in this paper. Location of sections depicted in later figures: red line, seismic profiles (Fig. 3); green line, synoptic diagrams (Figs. 4, 5); black line, well transects (Fig. 9).

Fig. 3. Seismic reflection data. Locations are shown in Figs. 2 and 6. N.B. vertical scales in s TWTT.

a. Migrated seismic reflection line NW-SE across Quadrant 109: JEBCO JS-MANX-138. Includes content supplied by IHS Global Limited. Copyright © IHS Global Limited (2016). All rights reserved. Note the considerable thickness of Carboniferous strata in the Eubonia Tilt-block, here exceeding 2.5 s TWTT; brighter reflectivity towards top of tilt-block below Intra-Visean unconformity possibly reflecting reefal development; and in the south, a northward-vergent anticline-thrust inversion couple, defining the northern edge of the Môn-Deemster Basin. The presence of Warwickshire Group strata is inferred from seismostratigraphic principles and has not yet been confirmed by drilling.

b. Arbitrary NNW-SSE line through the migrated 3D TerraCube® dataset, supplied courtesy of CGG GeoSpec. Note the presence of a series of inversion anticlines (Môn-Deemster Foldbelt) in the Carboniferous sequence, associated with thrusts (fault-plane reflections) which penetrate into the Caledonian basement. A less steeply dipping detachment is present at depth. The Bowland Shale Formation is inferred to occupy a rather transparent zone, sandwiched between more reflective Carboniferous Limestone Group (below) and Millstone Grit Group (above). The mildly deviated well 110/07b-6 proved 450 m of Bowland Shale Formation before terminating in strata of Pendleian age (unbottomed). Westphalian strata have been almost completely eroded following strong inversion during the earliest Variscan phase. Inversion anticlines of this generation were reactivated ‘posthumously’ by further compression during the Alpine Orogeny in Miocene time, producing more gentle anticlines in the Permo-Triassic cover, including the traps in the Ormskirk Sandstone Formation (Top SSG pick) hosting the Conwy, Douglas and other fields.

Fig. 4. Synoptic diagrams (‘cartoons’) to illustrate principal elements of the hydrocarbon system of the greater Irish Sea province. Locations are shown in Figs. 2 and 6. N.B. vertical scales in s TWTT. The basin names used are principally those of the Permo-Triassic EISB and contemporary basins, rather than those of the Carboniferous elements newly named here:

a. Principal elements of the hydrocarbon system in the Eubonia Basin and Q109 Arch. Transect is parallel to Fig. 3a and father east, into the Eubonia Basin.

b. Principal elements of the EISB from the Lagman Fault (north) to the Welsh margin (south). The northern part crosses from the Ogham Platform, to the Lagman and Keys basins, where Westphalian strata are almost completely removed, the West Deemster Basin and Deemster Platform.Note thickening of the Bowland Shale Formation beneath Deemster Platform, associated with the offshore extension of the Bowland Basin. The southern part crosses the Môn-Deemster Foldbelt and is virtually colinear with Fig. 3b.

c. Principal elements of the hydrocarbon system in the Peel Basin. Note that fault displacements appear to be largely of post-Permian age, indicating little if any syn-depositional thickening across the Visean carbonate platform. Post-Visean strata were only preserved on the Manx margin.

Fig. 5. Synoptic diagrams ('cartoons') to illustrate principal elements of the hydrocarbon system of the greater Irish Sea province. Locations are shown in Figs. 2 and 6. N.B. vertical scales in s TWTT. The basin names used are principally those of the Permo-Triassic EISB and contemporary basins, rather than those of the Carboniferous elements newly named here:

a. Principal elements of the hydrocarbon system in the eastern part of the Solway Firth Basin. Note the preservation of late Westphalian Warwickshire Group (Whitehaven Sandstone Formation) in the Cumbrian Coalfield adjacent to the Maryport Fault, and the axis of Alpine inversion significantly offset from the Variscan one. The Visean strata here are Border Group and Yoredale facies, with uncertain source potential.

b. Principal elements of the hydrocarbon system in the northern part of the EISB. The WSW-ENE transect crosses Variscan second phase inversion structures obliquely in the Ogham Inlier, western Keys Basin and the Cumbrian margin.

c. Principal elements of the hydrocarbon system in the southern part of the EISB. The W-E transect is located parallel to the southern edge of the Môn-Deemster Foldbelt, crossing some of the Variscan first inversion phase structures obliquely. N-S trending inversion structures of the second Variscan phase at the margins of the East Deemster Basin and on the Formby Platform are crossed obliquely. Note the excision of Westphalian strata on these inversion systems. Modified from Yaliz (1997; Figure 4).

Fig.6. Pre-Permian subcrop map showing key Variscan inversion structures (after Pharaoh et al. 2016b). Variscan inversion structures in Ogham Platform after Quirk & Kimbell (1997). Abbreviated structure names: DP, Deemster Platform; EDB, East Deemster Western Boundary Fault; FPF, Formby Point Fault; OP, Ogham Platform; RE, Ribble Estuary Inlier. Location of sections depicted in other figures: red line, seismic profiles (Fig. 3); green line, synoptic diagrams (Figs. 4, 5); black line, well transects (Fig. 9).Hydrocarbon fields from OGA website: http://data.ogauthority.opendata.arcgis.com/datasets/

Fig.7. Petroleum system elements in a north-south transect across the central part of the region

Fig.8. Pendleian palaeogeography showing the Bowland Shale source rock distribution and lateral varation with Millstone Grit facies (from Wakefield et al. 2016).

Fig. 9. Well transects (from Wakefield et al. 2016). Locations are shown in Figs. 2 and 6. a. N-S transect across the EISB from the Lagman Basin to Rhuddlan, onshore North Wales. Note the truncation of the Warwickshire Group north of Point of Ayr and condensation of the underlying Westphalian strata, southward onto the Cambrian margin. Also note the variation in the thickness of the Appleby Group. b. W-E transect across the centre of the EISB from 109/5-1 in the Eubonia Basin to Roosecote, onshore north Cumbria.

Fig.10. Seismic structure map in depth (metres sub-sea level) for the Intra-Namurian pick, equated with the base of the Millstone Grit Group. Location of abbreviated Permo-Triassic basinal features (for reference purposes), refer to key to Figure 2.

Fig.11. A summary of the available geochemical data for Bowland Shale Formation lithologies in well 110/07b-6 and 110/02b-10. Data sourced from released legacy reports. Note that no Oxygen Index data are available for well 110/07b-6, so the data in the Pseudo-Van Krevelen Plot (Figure 11b) is from well 110/02b-10 (Millstone Grit and Pennine Coal Measures groups).

Fig.12. Modelled burial history for 110/07b- 6 showing that the Bowland Shale source rock entered the main gas generation window in the late Cretaceous-early Cenozoic. The well terminates within the Bowland Shale Formation.

Fig.13. Cross plot of core porosity and permeability for East Irish Sea Basin samples. For key to abbreviations see Table 1, except for PLC, Pennine Lower Coal Measures and PMCM, Pennine Middle Coal Measures.

Table 1. Synthesis of petrophysical results by formation (from Hannis, 2016). NTG = Net reservoir thickness to gross formation thickness. Porosity and net-to-gross are expressed as a fraction. Minimum porosity in the log-derived porosity range is 0.05, the net reservoir porosity cut-off value. Permeability figures are in mD. Core porosity and permeability data are synthesised from legacy reports.

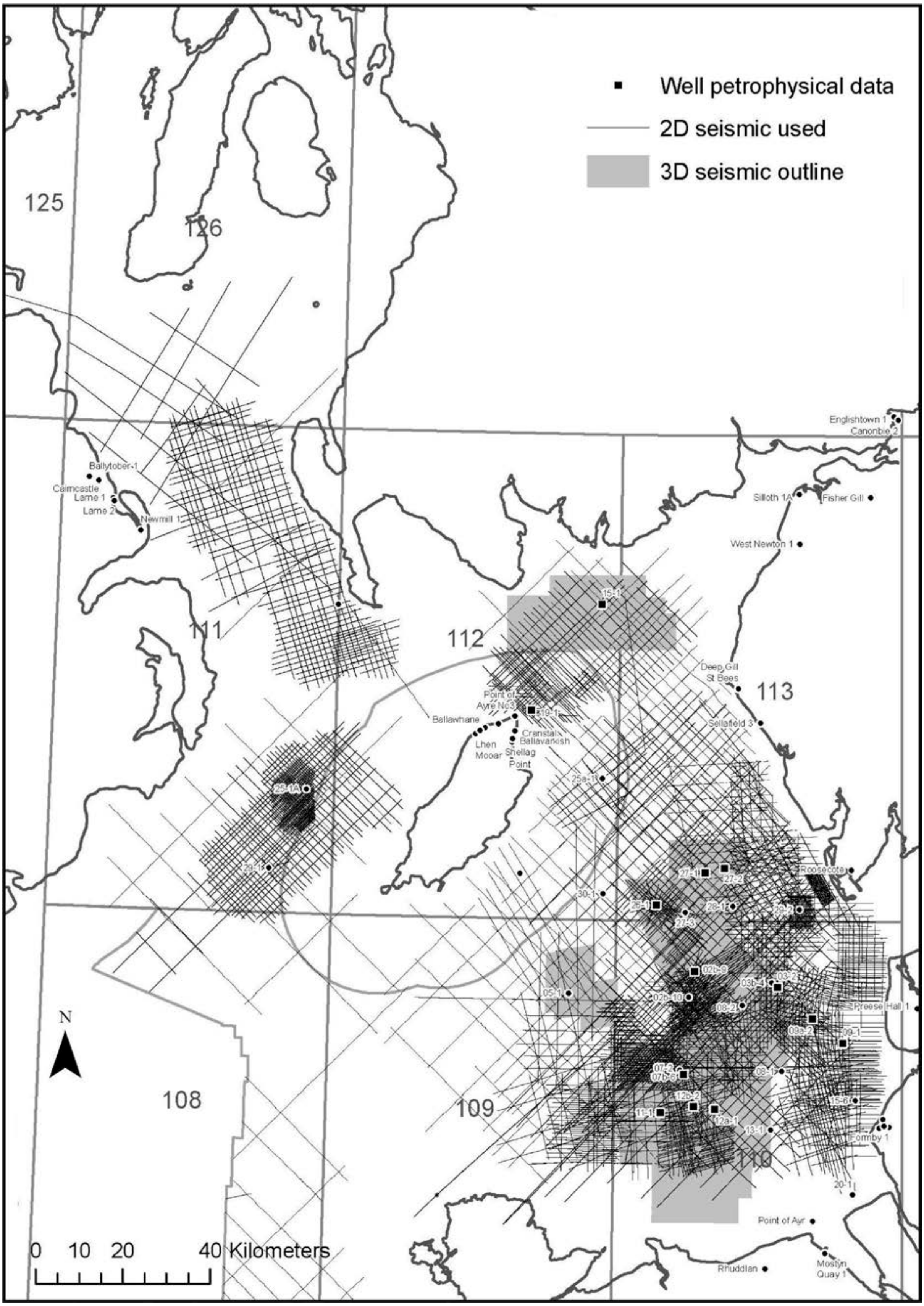

Well petrophysical data
2D seismic used
3D seismic outline
125
126
111
112
113
108
109
110
Englishtown 1
Canonbie 2
Ballytober-1
Cairncastle
Larne 1
Larne 2
Newmill 1
Silloth 1A
Fisher Gill
West Newton 1
15-1
Deep Gill
St Bees
Sellafield 3
Point of Ayre No3
19-1
Ballawhane
Cranstal
Lhen Mooar
Shellag Point
25-1A
29-1
30-1
Roosecote
27-1
27-2
26-1
27-3
29-2
02b-8
03b-4
05-1
02b-10
Preese Hall 1
09a-2
09-1
07-2
08-1
12b-2
11-1
12a-1
13-1
15-6
Formby 1
20-1
Point of Ayr
Rhuddlan
Mostyn Quay 1
N
0 10 20 40 Kilometers

Fig. 1

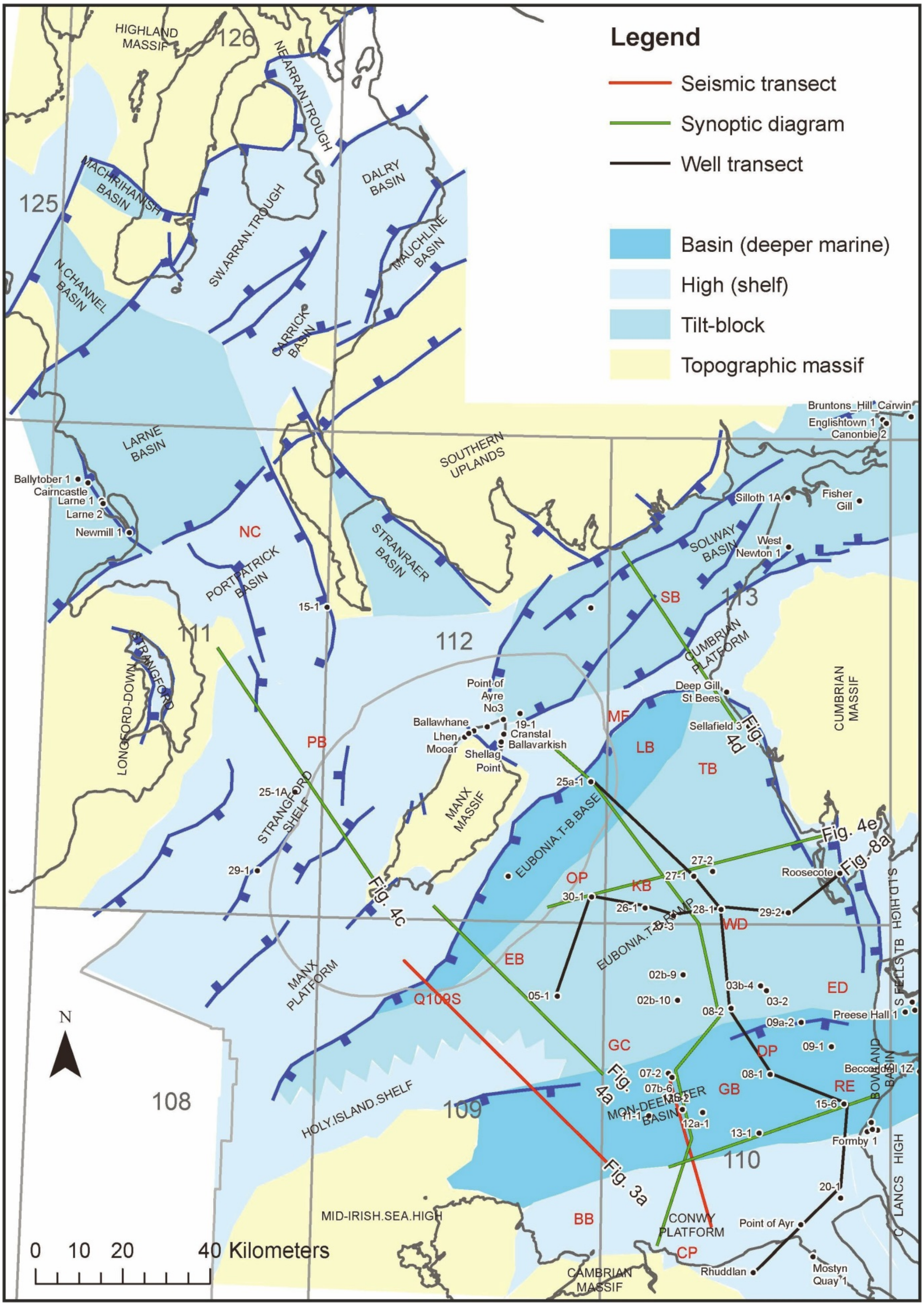
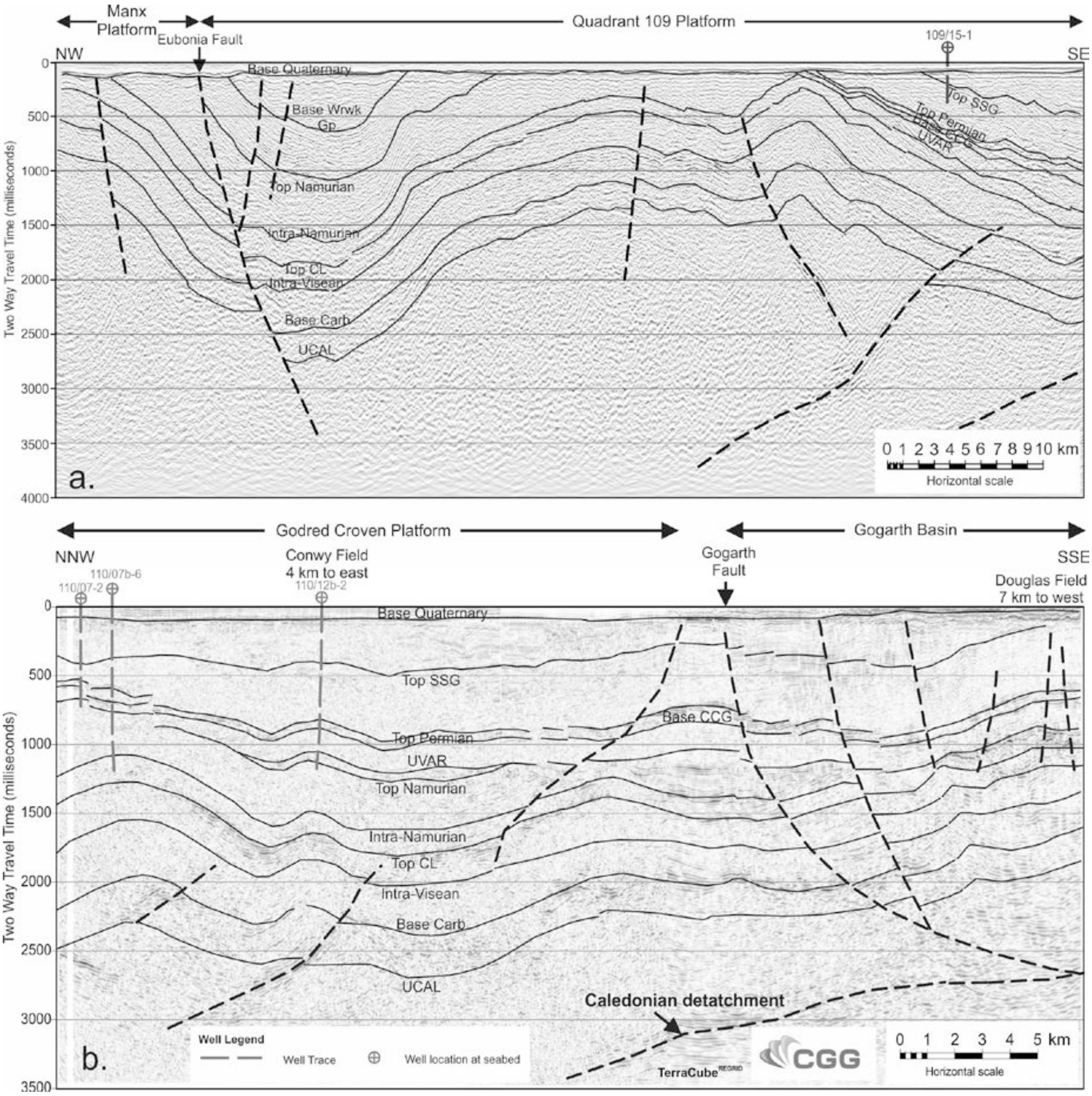
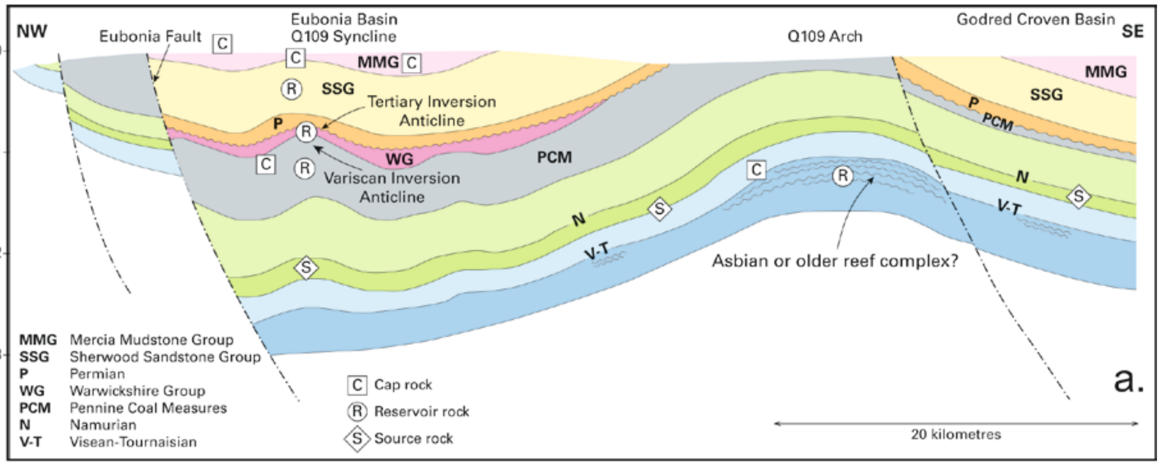

Legend
Seismic transect
Synoptic diagram
Well transect
Basin (deeper marine)
High (shelf)
Tilt-block
Topographic massif
HIGHLAND MASSIF
126
125
111
112
113
108
109
110
N.ARRAN.TROUGH
MACHRIHANISH BASIN
SW.ARRAN.TROUGH
DALRY BASIN
MAUCHLINE BASIN
N.CHANNEL BASIN
CARRICK BASIN
LARNE BASIN
SOUTHERN UPLANDS
PORTPATRICK BASIN
STRANRAER BASIN
SOLWAY BASIN
CUMBRIAN PLATFORM
CUMBRIAN MASSIF
STRANGFORD
LONGFORD-DOWN
STRANGFORD SHELF
MANX MASSIF
EUBONIA.T-B.BASE
EUBONIA.T-B.RAMP
MANX PLATFORM
HOLY.ISLAND.SHELF
MID-IRISH.SEA.HIGH
MON-DEE.TER BASIN
CONWY PLATFORM
CAMBRIAN MASSIF
BOWLAND BASIN
C. LANCS HIGH
NC
PB
SB
MF
LB
TB
OP
KB
WD
EB
ED
GC
DP
GB
RE
BB
CP
Q109S
Fig. 4c
Fig. 4d
Fig. 4e
Fig. 8a
Fig. 4a
Fig. 3a
Ballytober 1
Cairncastle
Larne 1
Larne 2
Newmill 1
15-1
25-1A
29-1
Point of Ayre No3
19-1
Ballawhane
Lhen
Mooar
Cranstal
Ballavarkish
Shellag Point
25a-1
Deep Gill
St Bees
Sellafield 3
Silloth 1A
Fisher Gill
West Newton 1
Bruntons_Hill_Carwin
Englishtown 1
Canonbie 2
27-2
27-1
30-1
26-1
28-1
29-2
Roosecote
02b-9
02b-10
05-1
03b-4
03-2
08-2
09a-2
Preese Hall 1
09-1
Beccanhill 1Z
07-2
07b-6
08-1
15-6
11-1
12a-1
13-1
Formby 1
20-1
Point of Ayr
Rhuddlan
Mostyn Quay 1
0 10 20 40 Kilometers
N

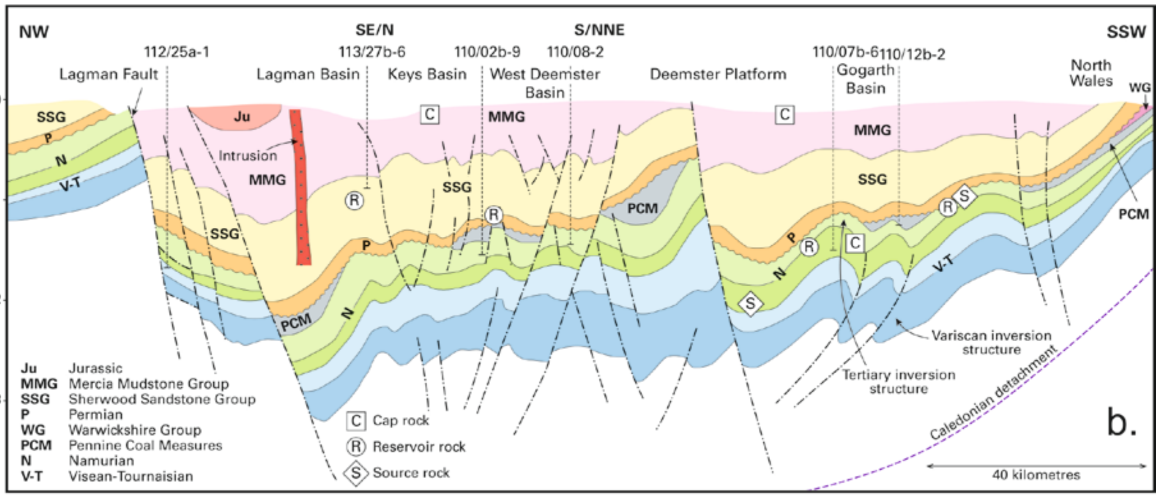
Fig. 2



Manx Platform
Quadrant 109 Platform
Eubonia Fault
109/15-1
NW
SE
Base Quaternary
Base Wrwk Gp
Top SSG
Top Permian
UVAR
Top Namurian
Intra-Namurian
Top CL
Intra-Visean
Base Carb
UCAL
Two Way Travel Time (milliseconds)
a.
0 1 2 3 4 5 6 7 8 9 10 km
Horizontal scale
Godred Croven Platform
Gogarth Basin
NNW
Conwy Field
4 km to east
Gogarth Fault
SSE
Douglas Field
7 km to west
110/07-2
110/07b-6
110/12b-2
Base Quaternary
Top SSG
Base CCG
Top Permian
UVAR
Top Namurian
Intra-Namurian
Top CL
Intra-Visean
Base Carb
UCAL
Caledonian detatchment
Well Legend
Well Trace
Well location at seabed
TerraCube
CGG
0 1 2 3 4 5 km
Horizontal scale
b.

Fig. 3 a, b


NW
Eubonia Fault
Eubonia Basin
Q109 Syncline
Q109 Arch
Godred Croven Basin
SE
MMG
SSG
P
WG
PCM
N
V-T
Tertiary Inversion Anticline
Variscan Inversion Anticline
Asbian or older reef complex?
TWTT (seconds)
MMG Mercia Mudstone Group
SSG Sherwood Sandstone Group
P Permian
WG Warwickshire Group
PCM Pennine Coal Measures
N Namurian
V-T Visean-Tournaisian
C Cap rock
R Reservoir rock
S Source rock
20 kilometres
a.


NW
SE/N
S/NNE
SSW
112/25a-1
113/27b-6
110/02b-9
110/08-2
110/07b-6
110/12b-2
Lagman Fault
Lagman Basin
Keys Basin
West Deemster Basin
Deemster Platform
Gogarth Basin
North Wales
Ju
Intrusion
MMG
SSG
PCM
WG
Variscan inversion structure
Tertiary inversion structure
Caledonian detachment
TWTT (seconds)
Ju Jurassic
MMG Mercia Mudstone Group
SSG Sherwood Sandstone Group
P Permian
WG Warwickshire Group
PCM Pennine Coal Measures
N Namurian
V-T Visean-Tournaisian
C Cap rock
R Reservoir rock
S Source rock
40 kilometres
b.

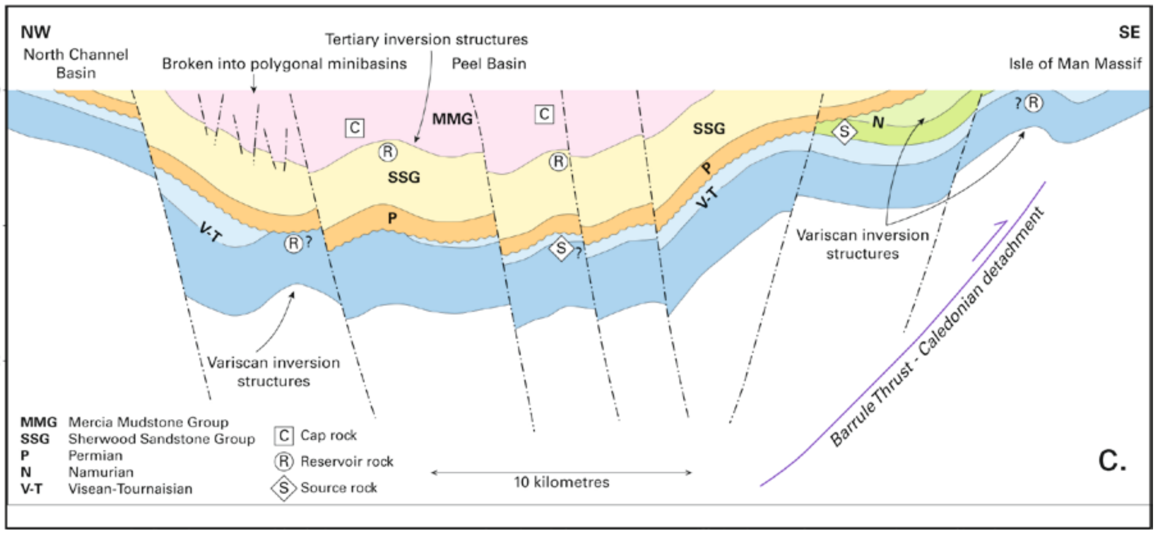

NW
SE
North Channel Basin
Broken into polygonal minibasins
Tertiary inversion structures
Peel Basin
Isle of Man Massif
MMG
SSG
P
V-T
N
Variscan inversion structures
Barrule Thrust - Caledonian detachment
TWTT (seconds)
MMG Mercia Mudstone Group
SSG Sherwood Sandstone Group
P Permian
N Namurian
V-T Visean-Tournaisian
C Cap rock
R Reservoir rock
S Source rock
10 kilometres
c.

Fig. 4a, b, c

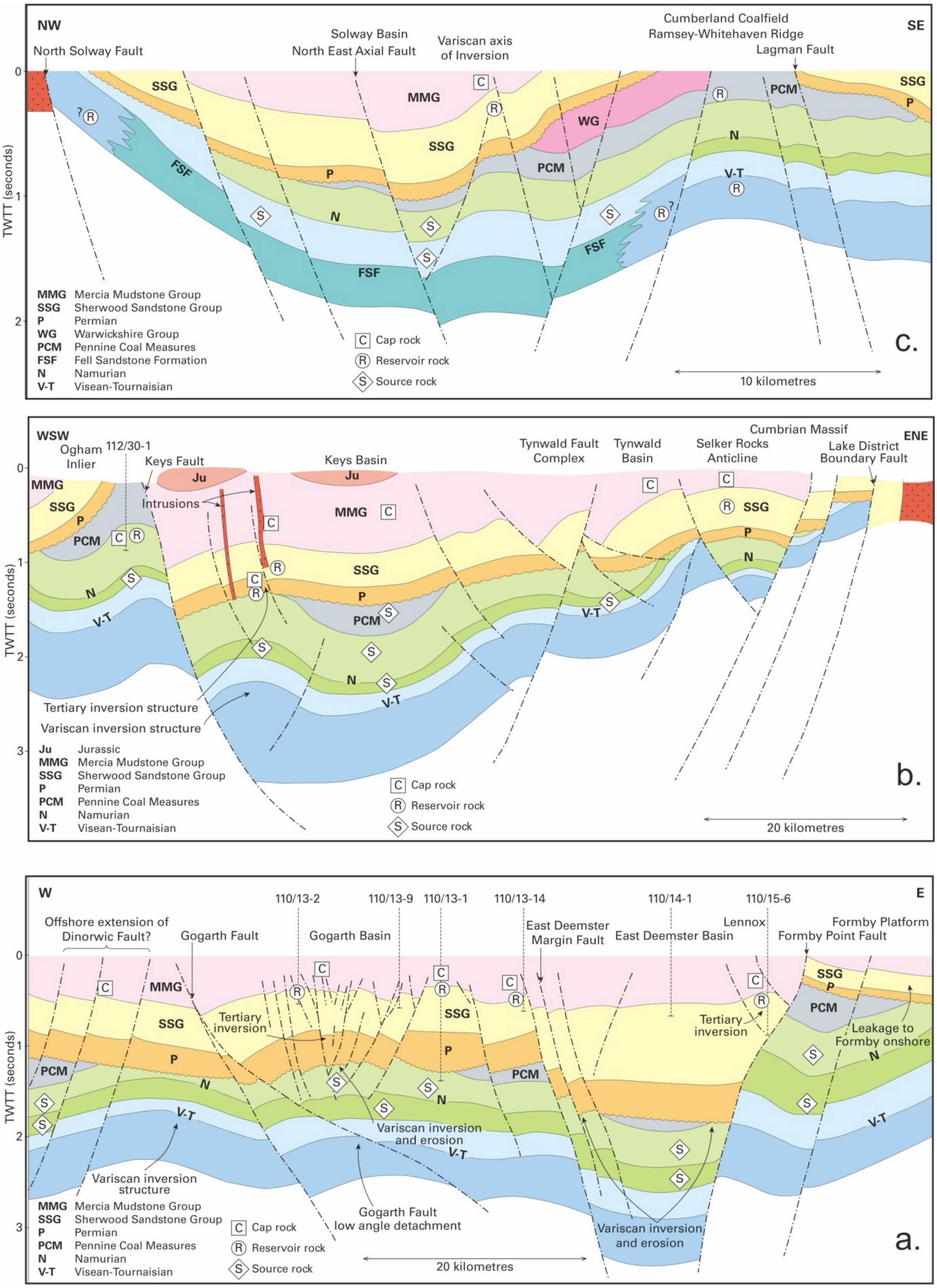
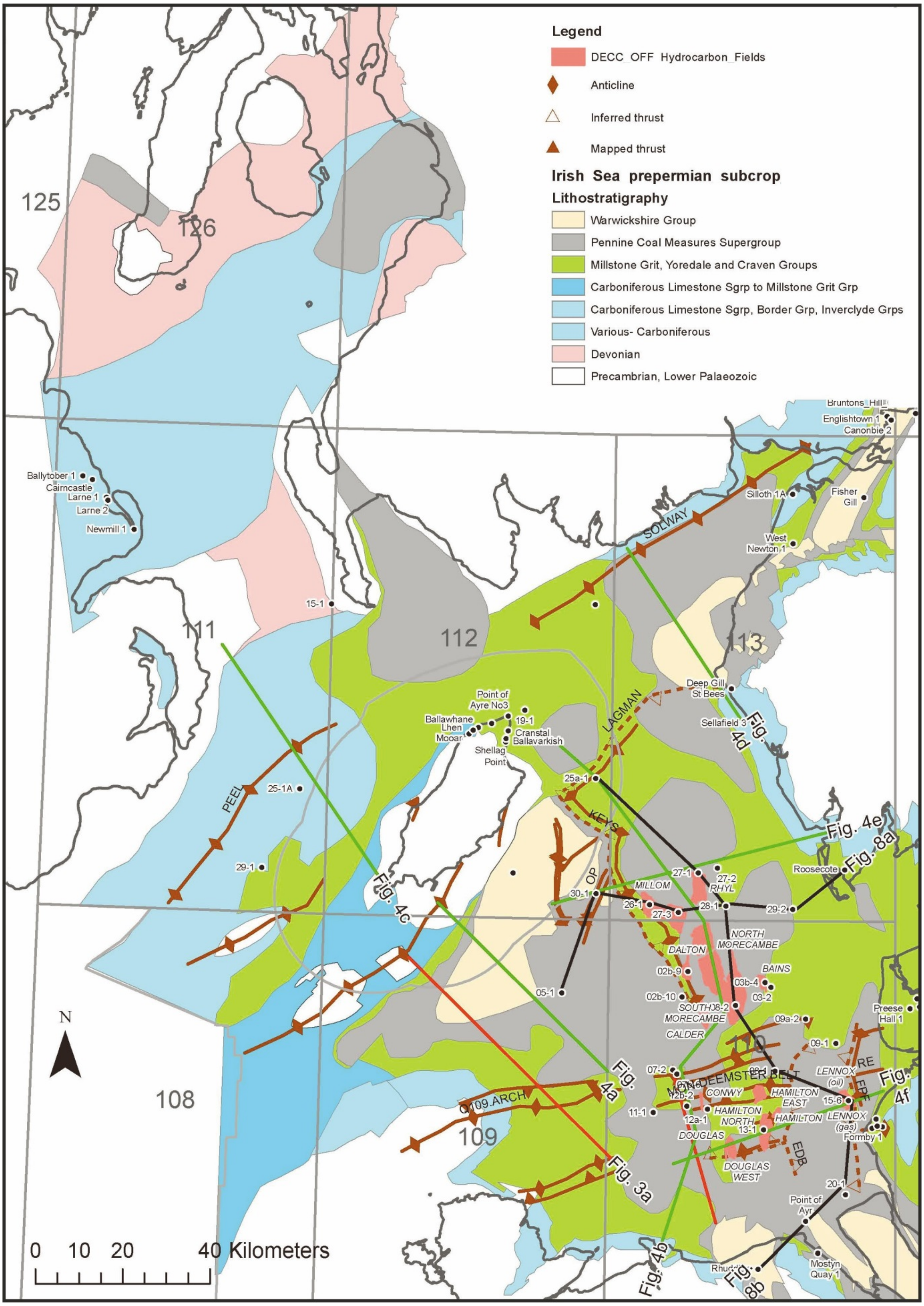
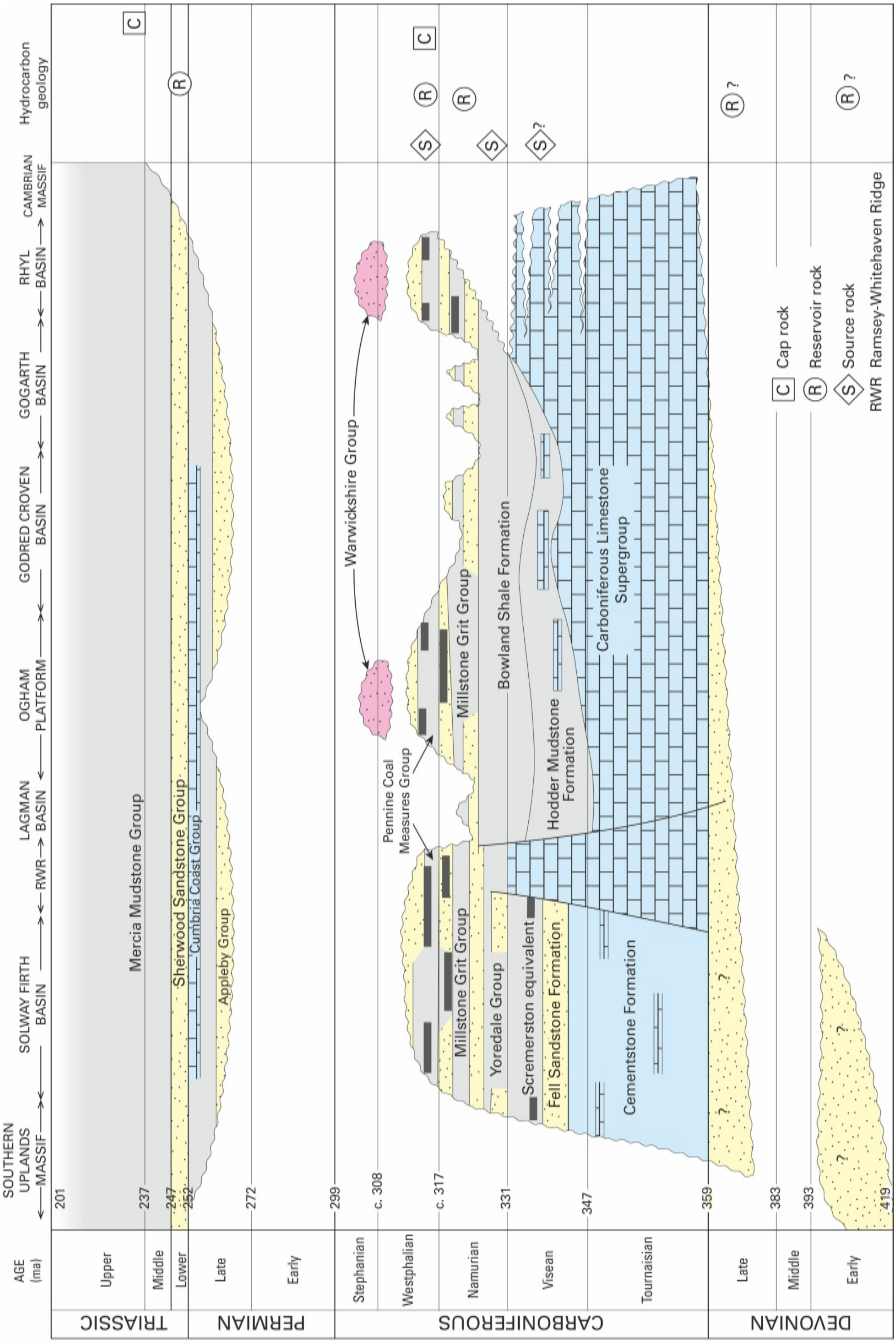

NW
SE
North Solway Fault
Solway Basin
North East Axial Fault
Variscan axis
of Inversion
Cumberland Coalfield
Ramsey-Whitehaven Ridge
Lagman Fault
TWTT (seconds)
MMG Mercia Mudstone Group
SSG Sherwood Sandstone Group
P Permian
WG Warwickshire Group
PCM Pennine Coal Measures
FSF Fell Sandstone Formation
N Namurian
V-T Visean-Tournaisian
Cap rock
Reservoir rock
Source rock
10 kilometres
c.
WSW
ENE
Ogham
Inlier
112/30-1
Keys Fault
Keys Basin
Intrusions
Tynwald Fault
Complex
Tynwald
Basin
Selker Rocks
Anticline
Cumbrian Massif
Lake District
Boundary Fault
Tertiary inversion structure
Variscan inversion structure
Ju Jurassic
MMG Mercia Mudstone Group
SSG Sherwood Sandstone Group
P Permian
PCM Pennine Coal Measures
N Namurian
V-T Visean-Tournaisian
Cap rock
Reservoir rock
Source rock
20 kilometres
b.
W
E
Offshore extension of
Dinorwic Fault?
Gogarth Fault
Gogarth Basin
110/13-2
110/13-9
110/13-1
110/13-14
East Deemster
Margin Fault
East Deemster Basin
110/14-1
110/15-6
Lennox
Formby Platform
Formby Point Fault
Tertiary
inversion
Leakage to
Formby onshore
Variscan inversion
and erosion
Variscan inversion
structure
Gogarth Fault
low angle detachment
MMG Mercia Mudstone Group
SSG Sherwood Sandstone Group
P Permian
PCM Pennine Coal Measures
N Namurian
V-T Visean-Tournaisian
Cap rock
Reservoir rock
Source rock
20 kilometres
a.

Fig. 5a, b, c



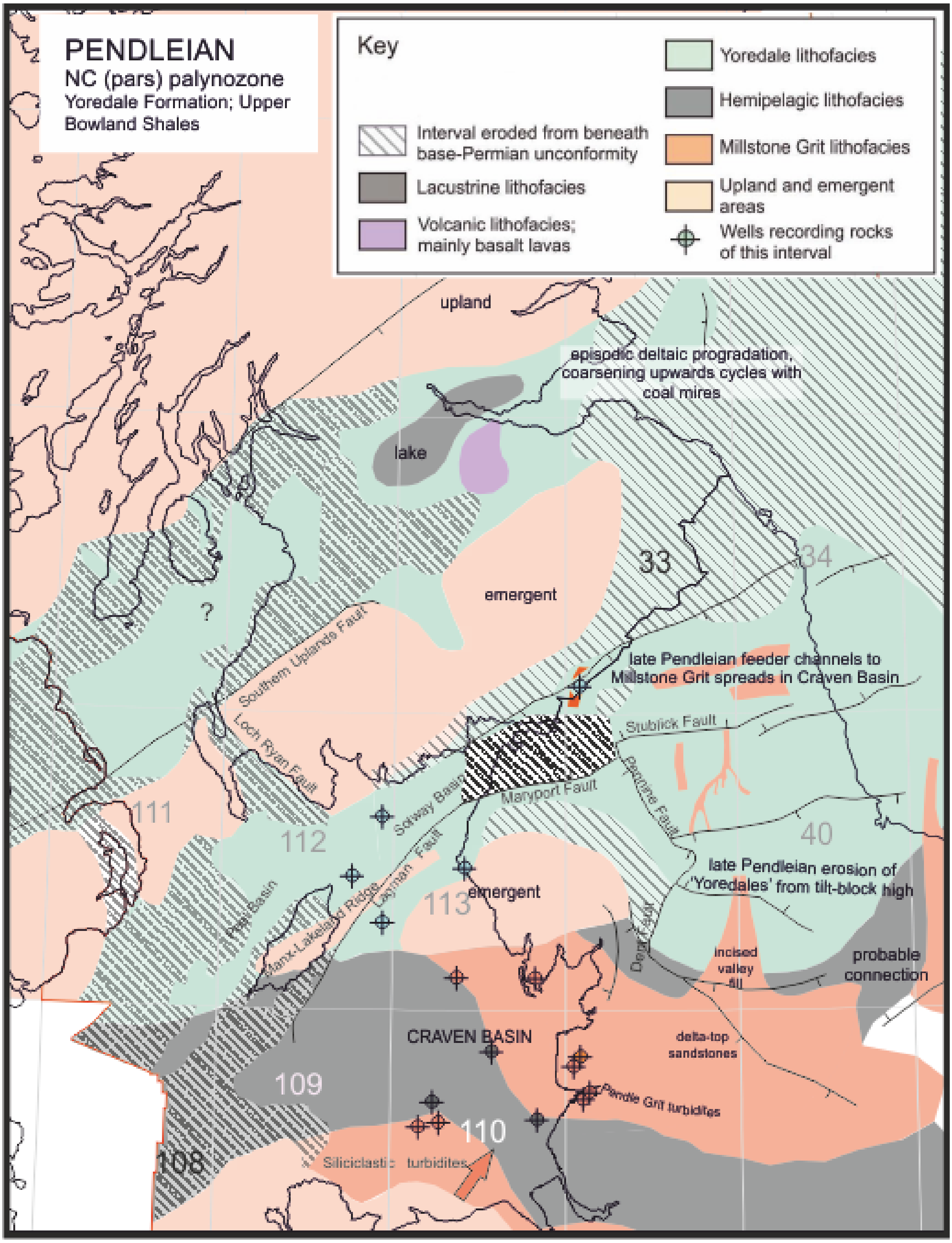
Legend
DECC OFF Hydrocarbon Fields
Anticline
Inferred thrust
Mapped thrust
Irish Sea prepermian subcrop
Lithostratigraphy
Warwickshire Group
Pennine Coal Measures Supergroup
Millstone Grit, Yoredale and Craven Groups
Carboniferous Limestone Sgrp to Millstone Grit Grp
Carboniferous Limestone Sgrp, Border Grp, Inverclyde Grps
Various- Carboniferous
Devonian
Precambrian, Lower Palaeozoic
125
126
111
112
113
108
109
N
0 10 20 40 Kilometers
SOLWAY
PEEL
LAGMAN
KEYS
MILLOM
RHYL
NORTH MORECAMBE
DALTON
BAINS
SOUTH MORECAMBE
CALDER
DEEMSTER BELT
CONWY
HAMILTON EAST
HAMILTON NORTH
HAMILTON
DOUGLAS
DOUGLAS WEST
LENNOX (oil)
LENNOX (gas)
EDB
109 ARCH
Fig. 4a
Fig. 4b
Fig. 4c
Fig. 4d
Fig. 4e
Fig. 4f
Fig. 3a
Fig. 8a
Fig. 8b
Ballytober 1
Cairncastle
Larne 1
Larne 2
Newmill 1
15-1
25-1A
29-1
Point of Ayre No3
19-1
Ballawhane
Lhen
Mooar
Cranstal
Ballavarkish
Shellag Point
25a-1
Deep Gill
St Bees
Sellafield 3
Silloth 1A
West Newton 1
Fisher Gill
Bruntons Hill
Englishtown 1
Canonbie 2
27-1
27-2
30-1
26-1
27-3
28-1
29-2
Roosecote
02b-9
02b-10
03b-4
03-2
05-1
09a-2
09-1
07-2
11-1
12a-1
13-1
15-6
Formby 1
Preese Hall 1
20-1
Point of Ayr
Mostyn Quay 1

Fig. 6



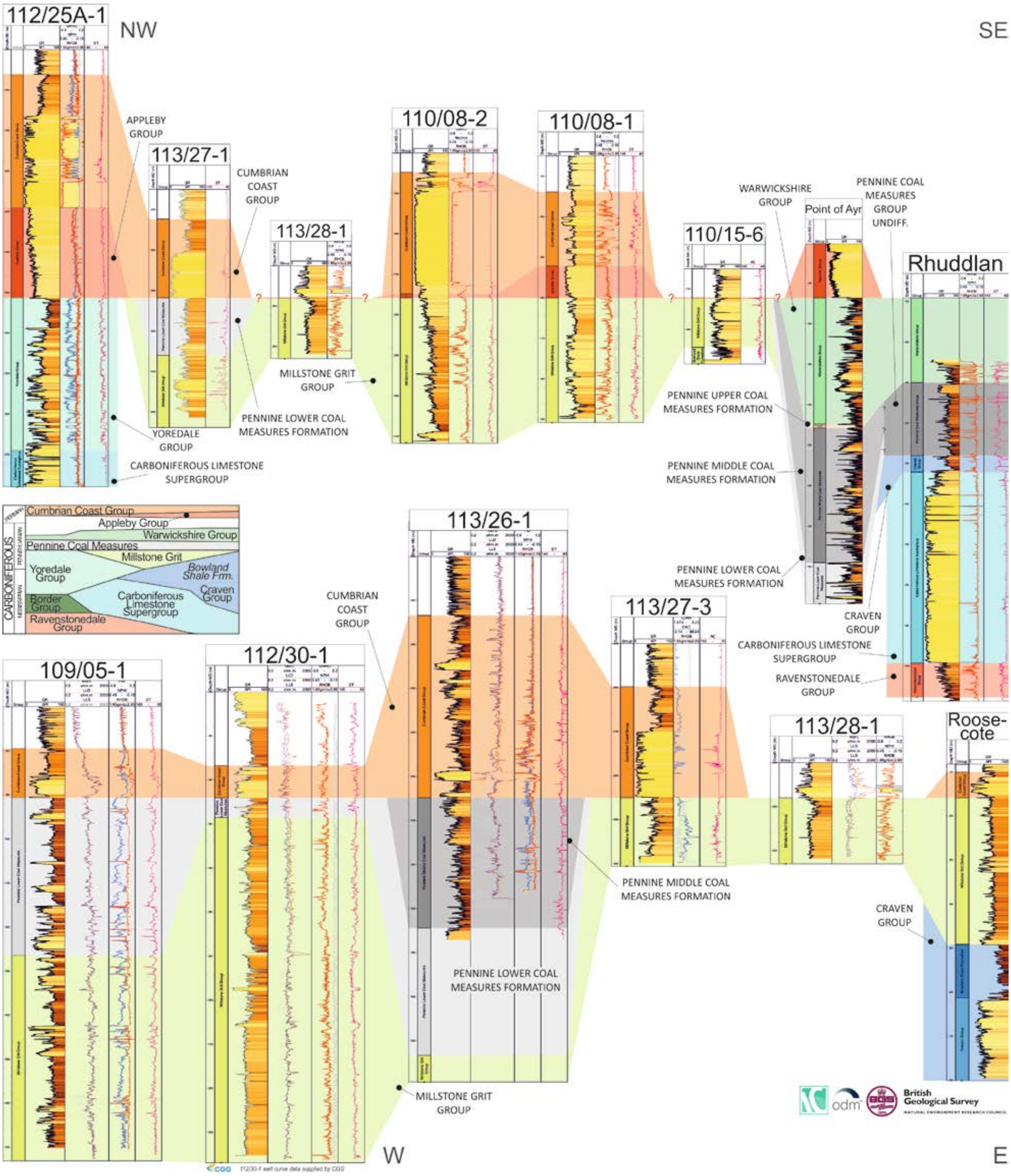
AGE (ma)
TRIASSIC
PERMIAN
CARBONIFEROUS
DEVONIAN
Upper
Middle
Lower
Late
Early
Stephanian
Westphalian
Namurian
Visean
Tournaisian
Late
Middle
Early
SOUTHERN UPLANDS MASSIF
SOLWAY FIRTH BASIN
RWR
LAGMAN BASIN
OGHAM PLATFORM
GODRED CROVEN BASIN
GOGARTH BASIN
RHYL BASIN
CAMBRIAN MASSIF
Hydrocarbon geology
201
237
247
252
272
299
c. 308
c. 317
331
347
359
383
393
419
Mercia Mudstone Group
Sherwood Sandstone Group
Cumbria Coast Group
Appleby Group
Warwickshire Group
Pennine Coal Measures Group
Millstone Grit Group
Yoredale Group
Scremerston equivalent
Fell Sandstone Formation
Cementstone Formation
Bowland Shale Formation
Hodder Mudstone Formation
Carboniferous Limestone Supergroup
C Cap rock
R Reservoir rock
S Source rock
RWR Ramsey-Whitehaven Ridge

Fig. 7



PENDLEIAN
NC (pars) palynozone
Yoredale Formation; Upper Bowland Shales
Key
Interval eroded from beneath base-Permian unconformity
Lacustrine lithofacies
Volcanic lithofacies; mainly basalt lavas
Yoredale lithofacies
Hemipelagic lithofacies
Millstone Grit lithofacies
Upland and emergent areas
Wells recording rocks of this interval
upland
episodic deltaic progradation, coarsening upwards cycles with coal mires
lake
emergent
33
34
?
Southern Uplands Fault
Loch Ryan Fault
late Pendleian feeder channels to Millstone Grit spreads in Craven Basin
Stublick Fault
Maryport Fault
Solway Basin
Pennine Fault
111
112
40
late Pendleian erosion of 'Yoredales' from tilt-block high
113
emergent
Manx-Lakeland Ridge
Lagman Fault
Peel Basin
Dent Fault
incised valley fill
probable connection
CRAVEN BASIN
delta-top sandstones
109
Pendle Grit turbidites
110
108
Siliciclastic turbidites

Fig. 8



112/25A-1
NW
SE
APPLEBY GROUP
113/27-1
CUMBRIAN COAST GROUP
113/28-1
110/08-2
110/08-1
WARWICKSHIRE GROUP
Point of Ayr
PENNINE COAL MEASURES GROUP UNDIFF.
110/15-6
Rhuddlan
MILLSTONE GRIT GROUP
PENNINE LOWER COAL MEASURES FORMATION
YOREDALE GROUP
CARBONIFEROUS LIMESTONE SUPERGROUP
PENNINE UPPER COAL MEASURES FORMATION
PENNINE MIDDLE COAL MEASURES FORMATION
PENNINE LOWER COAL MEASURES FORMATION
Cumbrian Coast Group
Appleby Group
Warwickshire Group
Pennine Coal Measures
Millstone Grit
Yoredale Group
Bowland Shale Frm.
Craven Group
Carboniferous Limestone Supergroup
Border Group
Ravenstonedale Group
CARBONIFEROUS
113/26-1
CUMBRIAN COAST GROUP
113/27-3
CRAVEN GROUP
CARBONIFEROUS LIMESTONE SUPERGROUP
RAVENSTONEDALE GROUP
109/05-1
112/30-1
113/28-1
Roose-cote
PENNINE MIDDLE COAL MEASURES FORMATION
CRAVEN GROUP
PENNINE LOWER COAL MEASURES FORMATION
MILLSTONE GRIT GROUP
British Geological Survey
W
E

Fig. 9a, b

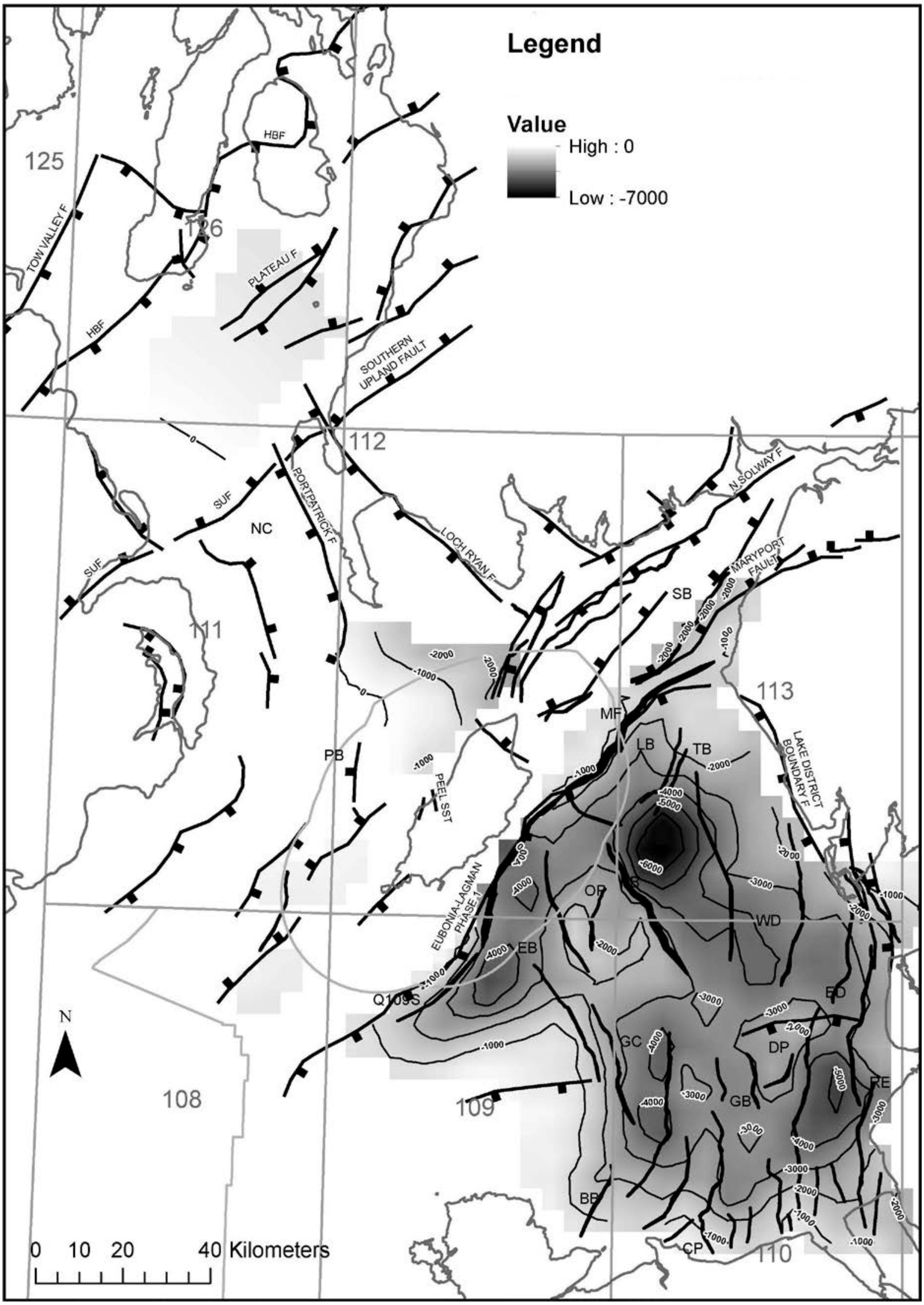

Legend
Value
High : 0
Low : -7000
125
126
112
111
113
108
109
110
TOW VALLEY F
HBF
PLATEAU F
SOUTHERN UPLAND FAULT
SUF
NC
PORTPATRICK F
LOCH RYAN F
N SOLWAY F
MARYPORT FAULT
SB
MF
LB
TB
PB
PEEL SST
LAKE DISTRICT BOUNDARY F
EUBONIA-LAGMAN PHASE 1
OP
WD
EB
Q109S
GC
DP
GB
FE
BB
CP
0 10 20 40 Kilometers
N

Fig. 10

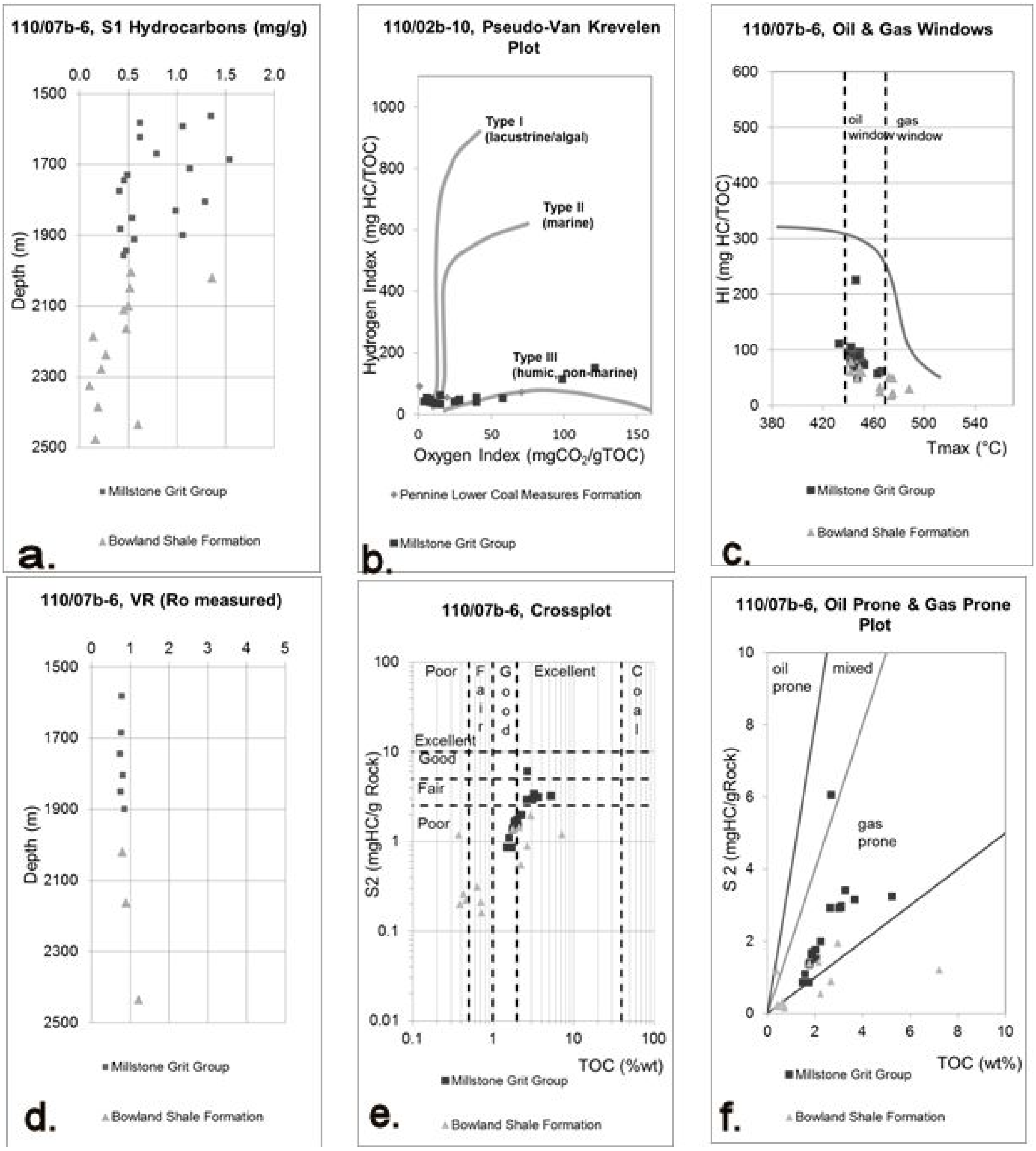

110/07b-6, S1 Hydrocarbons (mg/g)
Depth (m)
Millstone Grit Group
Bowland Shale Formation
a.
110/02b-10, Pseudo-Van Krevelen Plot
Type I (lacustrine/algal)
Type II (marine)
Type III (humic, non-marine)
Hydrogen Index (mg HC/TOC)
Oxygen Index (mgCO2/gTOC)
Pennine Lower Coal Measures Formation
Millstone Grit Group
b.
110/07b-6, Oil & Gas Windows
oil window
gas window
HI (mg HC/TOC)
Tmax (°C)
Millstone Grit Group
Bowland Shale Formation
c.
110/07b-6, VR (Ro measured)
Depth (m)
Millstone Grit Group
Bowland Shale Formation
d.
110/07b-6, Crossplot
Poor
Fair
Good
Excellent
Coal
S2 (mgHC/g Rock)
TOC (%wt)
Millstone Grit Group
Bowland Shale Formation
e.
110/07b-6, Oil Prone & Gas Prone Plot
oil prone
mixed
gas prone
S 2 (mgHC/gRock)
TOC (wt%)
Millstone Grit Group
Bowland Shale Formation
f.

Fig. 11

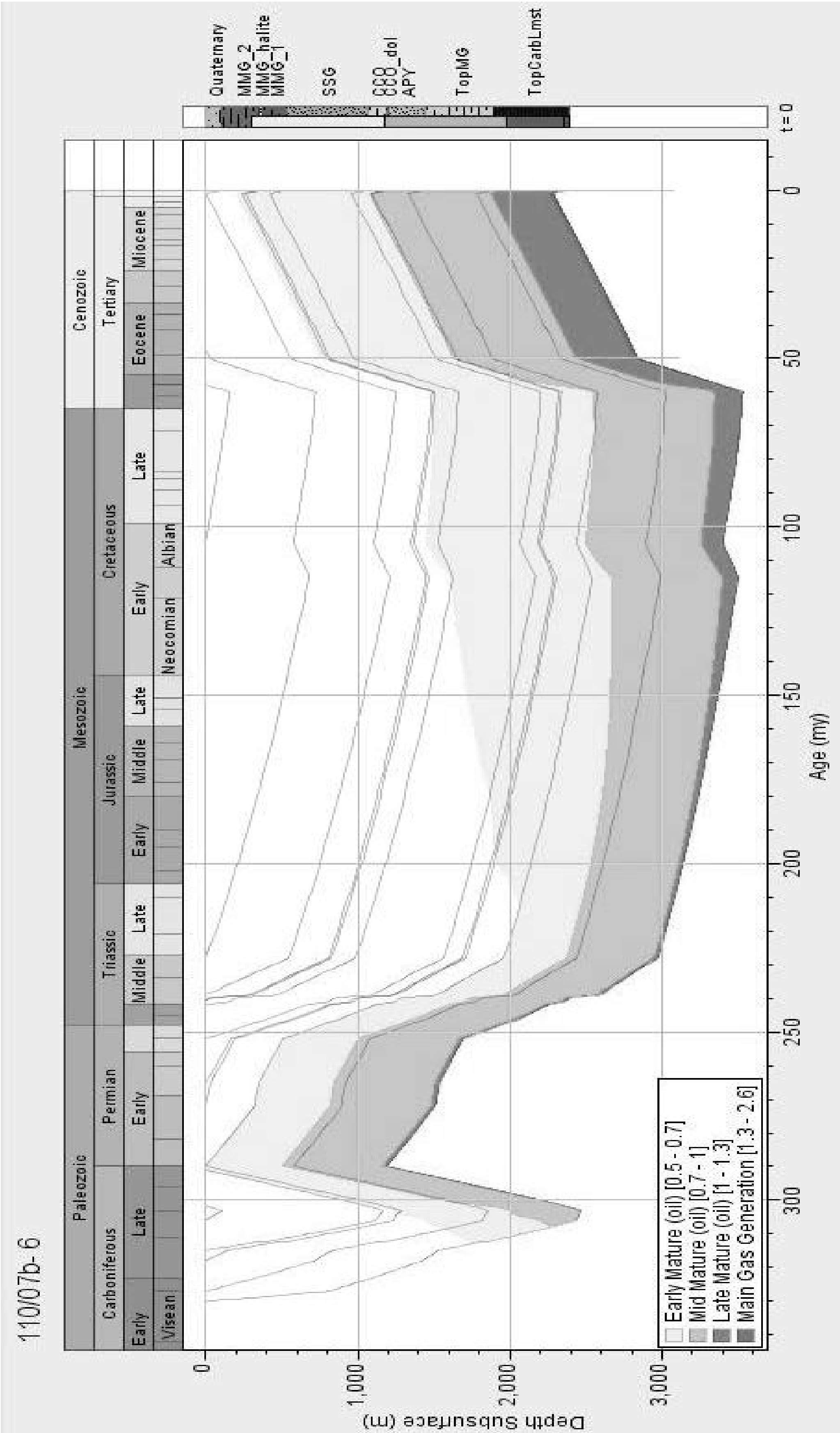
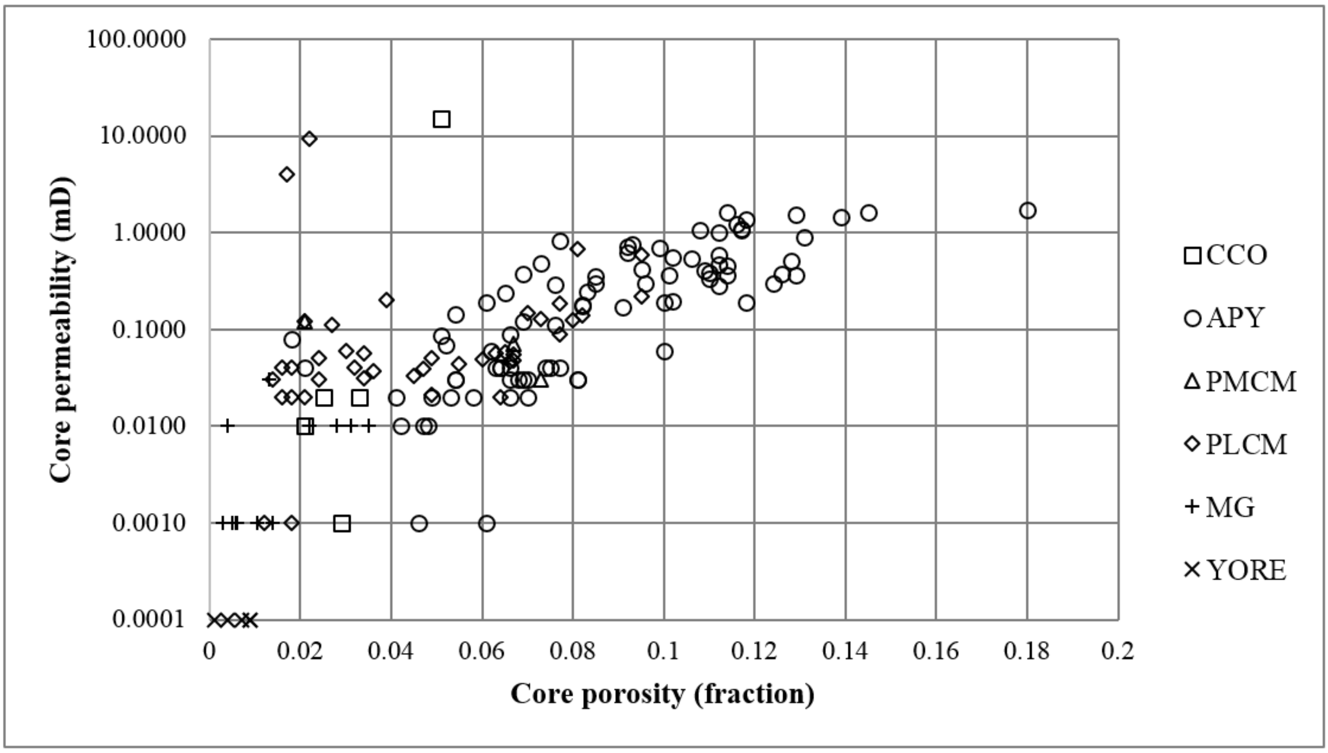

110/07b-6
Cenozoic
Mesozoic
Paleozoic
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Miocene
Eocene
Late
Early
Middle
Albian
Neocomian
Visean
Age (my)
Depth Subsurface (m)
0
1,000
2,000
3,000
50
100
150
200
250
300
t = 0
Quaternary
MMG_2
MMG_halite
MMG_1
SSG
APY
TopMG
TopCarbLmst
Early Mature (oil) [0.5 - 0.7]
Mid Mature (oil) [0.7 - 1]
Late Mature (oil) [1 - 1.3]
Main Gas Generation [1.3 - 2.6]

Fig. 12



Core permeability (mD)
100.0000
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Core porosity (fraction)
CCO
APY
PMCM
PLCM
MG
YORE

Fig. 13

		Log derived							Core measured							
											Highest Average		Permeability			
Stratigraphic unit name	Code	Net thickness (m)	NTG	Highest Average Porosity	Porosity range	Highest Average Permeability estimate	Permeability estimate range	*Metres of log*	Highest Average Porosity	Porosity range	horizontal (kh)	vertical (kv)	horizontal (kh)	vertical (kv)	*Samples*	Comments
Cumbrian Coast Group	CCO	81	0.07	0.14	0.05-0.43	0.17	0.02-1.39	*1197*	0.04	0.02-0.07	3.06		0.01-15.20		*6*	
Appleby Group	APY	936	0.79	0.19	0.05-0.40	6.89	0.17-82.27	*1191*	0.13	0.05-0.21	0.80	7.90	0.00-1.72	0.17-71.5	*154*	Highest net to gross, highest porosity. Highest permeabilities values in the 50-100 mD range for several wells.
Pennine Coal Measures Group	PCM	62	0.09	0.11	0.05-0.26	0.79	0.02-61.45	*795*	0.06	0.01-0.10	1.07	0.01	0.00-9.43	0.01-0.13	*55*	Low NTG (although third highest of the units examined). Reasonable average porosity. Permeabilities appear low. (Highest values of 61.4 mD in 1 well, but with no core data over that interval).
Millstone Grit Group	MG	293	0.10	0.11	0.05-0.31	367.74	0.17-10000	*2971*	0.06	0-0.10	0.04	0.05	0.00-0.37	0.00-0.13	*49*	Highest permeability (although estimated with low confidence: seen in only 1 of 3 wells (113/27-2), with a relatively poor core-log data fit). Low NTG (although second highest of the units examined).
Yoredale Group	YORE	16	0.02	0.07	0.05-0.30			*783*	0.01	0.00	0.00	0.00	0.00	0.00	*9*	
Bowland Shale Formation	BSG	16	0.03	0.07	0.05-0.23	0.75	0.15-16.19	*551*							*0*	
Carboniferous Limestone Supergroup	CL	0	0.00	0.05	0.05-0.05			*246*							*0*	Matrix porosities are less than 5% therefore the unit is not considered to have any 'net' using the cut offs applied.

Table 1

An overlooked play? Structure, stratigraphy and hydrocarbon prospectivity of the Carboniferous in the East Irish Sea-North Channel basin complex

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Abstract: Seismic mapping of key Palaeozoic surfaces in the East Irish Sea – North Channel region has been incorporated into a review of hydrocarbon prospectivity. The major Carboniferous basinal and inversion elements are identified, allowing an assessment of the principal kitchens for hydrocarbon generation and possible migration paths. A Carboniferous tilt-block is identified beneath the central part of the (Permian to Mesozoic) East Irish Sea Basin (EISB), bounded by carbonate platforms to south and north. The importance of the Bowland Shale Formation as the key source rock is reaffirmed, the Pennine Coal Measures having been extensively excised following Variscan inversion and pre-Permian erosion. Peak generation from the Bowland source coincided with maximum burial of the system in late Jurassic/early Cretaceous time. Multiphase Variscan inversion generated numerous structural traps whose potential remains underexplored. Leakage of hydrocarbons from these into the overlying Triassic Ormskirk Sandstone reservoirs is likely to have occurred on a number of occasions, but currently unknown is how much resource remains in place below the Base-Permian unconformity. Poor permeability in the Pennsylvanian strata beneath the Triassic fields is a significant risk; the same may not be true in the less deeply buried marginal areas of the EISB, where additional potential plays are present in Mississippian carbonate platforms and latest Pennsylvanian clastic sedimentary rocks. Outside the EISB, the North Channel, Solway and Peel basins also contain Devonian and/or Carboniferous rocks. There have however been no discoveries, largely a consequence of the absence of a high quality source rock and a regional seal comparable to the Mercia Mudstone Group and Permian evaporites of the Cumbrian Coast Group in the EISB.

The productive oil and gas fields of the EISB evidence a working, Carboniferous-sourced petroleum system. Whilst a great deal may be known of the Triassic reservoir and seal (Meadows *et al.* 1997), little is known about Carboniferous and Permian petroleum systems at depth and in adjacent basins, that may offer significant additional potential. The presence of a Palaeozoic hydrocarbon system in the East Midlands and southern North Sea is well documented however (Fraser *et al*. 1990; Fraser & Gawthorpe 2003; Besly 1998). Following the Wood Review (2014), Palaeozoic plays, including that of the greater Irish Sea area were identified as priority for building regional digital datasets and stimulating exploration. In response, the *21st Century Exploration Roadmap: Palaeozoic Project* running from 2014-2016 and openly released in 2017, undertook regional scale seismic and well interpretation, source and reservoir screening studies and basin modelling. This paper provides a re-interpretation of the structural history of the greater Irish Sea, and its influence on potential Carboniferous and Permian prospectivity including the marginal basins.

The Carboniferous structure and stratigraphy of the UK sector of the East Irish Sea-North Channel region has been reviewed using all available well and seismic reflection data. The project interpreted about 40,000 km of 2D seismic data of many vintages from 1980-2000, with local infill from 3D data, to generate time and depth-converted surfaces for key Palaeozoic horizons (Pharaoh *et al.* 2016a). Priority was given to the interpretation of long regional speculative lines, with infill from licence- and prospect-scale surveys. These surfaces were then used as the basis for an assessment of Palaeozoic hydrocarbon prospectivity (Pharaoh *et al.* 2016b), which forms the core of this paper. For brevity, the seismic interpretations are summarised using synoptic diagrams ('cartoons'). The present economic focus of the hydrocarbon province is the Morecambe Bay gasfield and its satellites, located within the EISB, a basin complex of Permian to Mesozoic age comprising a number of mainly N-S oriented graben and intervening platforms (BGS 1994; Jackson *et al.* 1987, 1995, 1997). Together with the Worcester Graben and Cheshire Basin of the UK onshore, it forms part of the major Permian rift system extending through the north European province of the Pangaea Supercontinent (Ziegler 1990; Coward 1995; Chadwick & Evans 1995; Scheck-Wenderoth *et al*. 2008). The principal structures of the EISB are strongly discordant to those in the pre-Permian substrate, which bear the imprint of a long and complex evolution culminating in the Variscan Orogeny in latest Carboniferous time. For these Devonian and Carboniferous tectonic elements, a new terminology is presented here and the lithostratigraphical nomenclature of Waters *et al.* (2011) is used to integrate onshore and offshore successions, allowing more precise correlation than the scheme introduced by Jackson *et al.* (1997).

The Bowland Shale Formation is recognised as a prolific source of gas for the Permo-Triassic reservoirs (Armstrong *et al.* 1997), but potential Namurian and Westphalian reservoirs suffer from low porosity and permeability due to the combined effects of Variscan inversion, deep burial in a Permian-Mesozoic rift, Cenozoic inversion, magmatism and thermal effects associated with the rifting of the North Atlantic (Meadows *et al.* 1997; Quirk & Kimbell 1997). Several areas on the margins of the EISB (Manx-Furness Ridge, Cumbrian margin, Fylde margin, Cambrian margin) are underlain by the offshore extensions of onshore coalfields or Namurian strata. These areas are covered in some detail by seismic data, and the availability of onshore analogues allows a more realistic assessment in terms of potential for development of non-conventional resources, perhaps from coastal locations.

Methodology and datasets

The exploration datasets used in the regional interpretation are depicted in Fig. 1. The 2D seismic datasets include regional speculative data supplied by geophysical companies (CGG, IHS and WesternGeco); licence- and prospect-level datasets provided by the Common Data Access Initiative (CDA) offshore and United Kingdom Onshore Geophysical Library (UKOGL) nearshore and onshore; and data supplied directly by participating companies (Centrica plc). The 3D dataset used was supplied by CDA, augmented by data from the 3D Terracube supplied by CGG. The well picks were supplied from the DECC well database at BGS Edinburgh, with further interpretation during the project.

Pre-Carboniferous structural evolution

The crust of the southern part of the region (North Wales, Anglesey and adjacent offshore areas (Fig. 2) was generated as volcanic and sedimentary complexes in magmatic arc-trench systems during late Proterozoic time. Many early tectonic lineaments (e.g. the Menai Strait Fault Zone; Gibbons 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 in 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 (Smith *et al.* 1999; Chew & Strachan 2014). Its southern limit is marked by the Highland Boundary Fault, which forms the northern boundary of the area of investigation.

The crust in the central part of the region 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 (Bluck 2002; Barnes *et al.* 2006; Chew & Strachan 2014). 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 Ribblesdale Foldbelt (Kirby *et al*. 2000); the Causey Pike Thrust and Southern Borrowdale Lineament of the Lake District (Barnes *et al.* 2006); the numerous accretionary tracts of the Southern Uplands massif (Bluck 2002); and numerous faults with this trend within the Southern Highlands terrane (Chew & Strachan 2014).

In this study, a NW-dipping zone of enhanced reflectivity in pre-Carboniferous 'basement', previously referred to as the Barrule Thrust (Chadwick *et al.* 2001), was mapped over a large area to NW of the Isle of Man. The analysis of the deep seismic reflection data presented by England & Soper (1997) suggests that this structure lies within the Avalonian footwall of the Iapetus Suture, rather than representing the suture itself. A further zone of NNW-dipping basement reflectivity underlies the southern part of the EISB (Jackson & Mulholland 1993; Pharaoh *et al.* 2016a; 2016b), being particularly prominent beneath the Conwy Platform, just off the north coast of Wales (Fig. 2). The dip of this zone steepens as it approaches the coast, and it is inferred to correlate with the southernmost strands of the Menai Strait Lineament, i.e. the Menai and Dinorwic fault zones. Although the seismic coverage is relatively poor in this area, the available data suggest that this zone represents the deepest regional detachment, with all subsequent extensional faulting (of Carboniferous and Permian-Mesozoic age) penetrating no deeper into the crust.

During the Acadian Phase of the Caledonian Orogeny, most 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 (Chew & Strachan 2014). 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, in the Midland Valley and form the molasse to the Caledonian Orogen (Trewin & Thirlwall 2002). In the south (Anglesey), Devonian strata are more limited in development and related to local faulted basin margins (Hillier & Williams 2006). In this tectonic regime, W-E extension is anticipated (Coward 1993). 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 rift basins (North Channel, Stranraer, Carlingford Lough) within the Southern Uplands Massif, and the Peel Sandstone Graben of the Isle of Man (Maddox *et al.* 1997; Parnell 1997; Quirk & Kimbell 1997).

Carboniferous structural and stratigraphic evolution

An extensional- transtensional tectonic regime persisted into Carboniferous time (Leslie *et al.* 2016). Although a general W-E extensional regime has been invoked in Mississippian time (Coward 1993), 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 Paola *et al.* 2005). This 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.* 1995), and is controlled by major bounding faults on a SW-NE trend. The Peel Basin along strike to the SW, has a similar trend but opposite structural polarity and a very different basin setting in the Carboniferous (Fig. 2). 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 extensional basins

The Carboniferous substrate of the EISB comprises a number of basin elements, comparable to that of the UK onshore. Fig. 2 presents a speculative reconstruction of the principal tectonic elements in Mississippian time. It is based heavily on seismostratigraphic and structural interpretation, as only five offshore boreholes penetrate Visean strata in the whole of the province (112/25a-1 and 113/27-2 in the EISB; 111/25-1A and 111/29-1 in the Peel Basin; and 112/19-1 in the Solway Basin, Fig. 2). In the centre of the EISB, a major basin, here referred to as the Eubonia Tilt-Block (Fig. 2), is inferred to extend from the Quadrant 109 (Q109) Syncline in the SW (BGS 1994) to the Ogham Platform (Fig. 2). Extension farther east, beneath the Lagman and Tynwald (Permian-Mesozoic) basins of the EISB, towards the western edge of the Lake District, is also inferred. The presence of a major half-graben (tilt-block), controlled by a major syndepositional bounding fault on its NW margin, the Eubonia-Lagman Fault System (Fig. 2, 3a), is indicated by the seismic reflection data. The structure was not identified as a tilt-block by Jackson & Mulholland (1993; p800), but they did recognise the marked asymmetry of the northern limb of the Q109 Syncline/Basin and the presence of up to 7.5 km of Visean to late Westphalian (and possibly Stephanian) strata. Fig. 3a shows a seismic line extending SE from the Isle of Man towards Anglesey (Fig. 2). It demonstrates the presence of over 2.5 s Two-Way Travel Time (TWTT) of Carboniferous strata east of the Eubonia Fault, in what is referred to as the Eubonia Tilt-block (Pharaoh *et al.* 2016b). Poor well control is provided by a few distant wells on the western edge of the EISB (Fig. 2) and the picks are not well constrained.

Towards the top of the tilt-block in the south, on the Holy Island Shelf, brighter reflectivity in the upper Visean interval, may represent the development of reefal carbonates. The southern end of the section crosses a northward-vergent inversion anticline-thrust couple, defining the northern limit of the Môn-Deemster Fold Belt. This is a 25-30 km wide belt of strong Variscan inversion, extending ENE from the north coast of Anglesey, from the Q109 Arch to the Deemster Platform (Fig. 2). The internal structure of this belt is imaged on numerous N-S profiles crossing the Godred Croven Basin, and Fig. 3b, an arbitrary line through 3D data in this area, is representative. A schematic profile is presented in Fig. 4b. A series of parallel WSW-ENE trending anticlinal folds has been mapped through the area. The internal structure of this inversion belt is complex, comprising a fan-like array of anticlines and synclines with associated thrusts, SSE-vergent in the south, and NNW-vergent in the north (Fig. 4b). Fig. 3b clearly shows discordant reflections in the Visean sequence, extending down into the Caledonian basement, interpreted here as fault-plane reflections. Below 3s TWTT, a further zone of intra-basement reflectivity is interpreted as a deeper Caledonian detachment surface, as recognised by Jackson & Mullholland (1993; p805). Well 110/07b- 6 was clearly a test of the structure with the greatest amplitude, at the northern end of the profile. This slightly deviated well proved 450 m of (presumed) Namurian Bowland Shale Formation (Pendleian unbottomed) beneath 550 m of Millstone Grit Group, Westphalian strata being absent beneath the Base-Permian unconformity (Fig. 3b). As noted above, northward-vergent structures have been identified on the northern edge of the Q109 Arch (Fig. 3a), and they have also been mapped beneath the northern part of the Deemster Platform. Several NNW-SSE to N-S trending graben of the EISB (Godred Croven, Gogarth and East Deemster basins) discordantly overlie this Carboniferous hinge-zone. The inversion belt is very similar in its structure and orientation to the Ribblesdale Foldbelt of the Lancashire onshore, representing the Variscan-inverted Bowland Basin (Corfield *et al.* 1996; Kirby *et al.* 2000). It seems logical to infer connection of the two, via the Fylde coast of Lancashire, as proposed by Corfield *et al*. (1996). If this inference is true, then the southern edge of the zone may represent a reactivated extensional fault, analogous to the Pendle Lineament of Lancashire; and the Visean carbonate platform (Holy Island and Conwy platforms) to the south, with a thin or absent Namurian cover, are the equivalent of the Central Lancashire High (Kirby *et al*. 2000). Also by analogy with the Bowland Basin/Ribblesdale Fold belt onshore, the greatest thickness of Bowland Shale offshore was probably deposited within a rift basin ancestral to the presently observed Môn-Deemster inversion zone. Further seismic mapping is required to confirm this however.

That part of the Eubonia Tilt-block lying east of the Keys Fault was subsequently almost obliterated by the combined effects of latest Variscan inversion and pre-Permian erosion. The original eastern limit of the tilt-block is uncertain. It likely continued beyond the Tynwald Basin, where the *en-echelon* faults of the Lake District Boundary Fault System may have acted as transfer faults, offsetting extensional subsidence farther south into the Craven Basin. On the northern margin of the tilt-block, to NW of the Eubonia-Lagman

Fault System, an extensive shallow marine carbonate platform developed in Visean time. This is well represented by outcrop in the south of the Isle of Man (Chadwick *et al*. 2001), the northern edge of the Lake District and adjacent offshore (Ramsey-Whitehaven Ridge) (Fig. 2). Because of significant pre-Permian uplift and erosion, it is not possible to determine the subsidence regime in which Westphalian strata were deposited, but it was probably dominated by post-extensional thermal subsidence, as elsewhere in southern Britain, the depocentre lying near Manchester (Fraser *et al.* 1990; Fraser & Gawthorpe *et al.* 1990).

A few wells penetrate the Carboniferous sequence beneath the Peel Basin (Fig. 2) and demonstrate that an extensive carbonate platform (Manx Platform and Strangford Shelf) extends west to Ireland and north towards the North Channel. The present study revealed that the undifferentiated Carboniferous strata on BGS (1994) mapping are principally of Visean age, Namurian strata being largely eroded (Pharaoh *et al.* 2016a). The Permo-Triassic Peel Basin has the form of an asymmetrical graben controlled by a major bounding fault on the northern side (Fig. 4c), and extensional faults with smaller throws on the southern side, developed in the hangingwall of the Barrule Thrust (Chadwick *et al.* 2001). Lack of evidence for significant Carboniferous syndepositional throw, and the larger Permo-Triassic throws, suggests that there was probably not a significant basin here in Visean time, although the poor quality of the seismic data allows some uncertainty. Faulting at the top of the Appleby Group (Permian) has a predominantly NW-SE trend (Quirk *et al.* 1999), akin to that of the North Channel Basin.

In contrast, the Solway Basin, underlying the Permian-Mesozoic Carlisle Basin along strike to NE of the Peel Basin, is asymmetrical with a principal controlling fault on the southern side (Ramsey-Whitehaven Ridge) (Fig. 5a). The Carboniferous basin fill comprises fluviodeltaic Border and Yoredale Group strata with greater affinity to the Northumberland Trough sedimentary sequence than the carbonate platforms of the southern Irish Sea (Chadwick *et al.* 1995), together with a greater thickness of preserved Pennsylvanian strata.

The present study found no convincing evidence for the presence of significant thicknesses of Carboniferous strata beneath Permo-Trias in the Portpatrick Basin, the southern part of the North Channel Basin complex: the only well to penetrate Permian in this basin (111/15-1) unfortunately terminated in early Palaeozoic rocks having passed through the marginal fault. The absence of Carboniferous strata may be a consequence of erosion following late Variscan inversion on the NNW-trend (see below). However, they are present within re-entrants at the northern edge of the Southern Upland Massif (Stranraer, Strangford Lough), and are certainly present to north of the Southern Upland Fault (Larne, Rathlin basins and SW Arran Trough). All of these basins are very poorly explored by deep boreholes and only very general conclusions can be made about their Mississippian evolution, largely by inference from nearby analogues onshore (Read *et al.* 2002).

Early phase of Variscan inversion

Through Pennsylvanian 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 northward thrust and nappe emplacement occurred in southern Britain, S Wales and S Ireland, but the region lay in the northern foreland of the Variscan Foldbelt (Besly 1988; Ziegler 1990; Pharaoh *et al.* 2010). In late Pennsylvanian (Westphalian C) time, an early phase of inversion was followed by deposition of strata of the Warwickshire Group, above a regional unconformity (Eastwood *et al.* 1937; Akhurst *et al.* 1997; Jones *et al.* 2011; Dean *et al.* 2011; Waters *et al.* 2011). The Whitehaven Sandstone Formation (equivalent to the Warwickshire Group and of latest Westphalian to ?Stephanian age) has divergent palaeocurrents to the south in Cumbria, and to the north at Canonbie, reflecting penecontemporaneous growth of the Solway inversion anticline (Jones *et al.* 2011). In the EISB, this study has identified SSW-ENE trending inversion structures parallel to the Eubonia-Lagman Fault System in the north (Fig. 6), as well as in the Môn-Deemster inversion belt described above. The study has shown that the early phase of Variscan inversion structures are cut discordantly by the NNW-SSE to N-S trending faults of the Permian-Mesozoic main graben structures of the EISB, such as the Keys Fault, Godred Croven Fault and western marginal 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, prior to deposition of Warwickshire Group strata (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).

Later phase of Variscan inversion

In late Pennsylvanian time, the final deformation phases of the Variscan Orogeny are associated with the closure of the Uralian Ocean basin and collision of the Kazakhstan and Siberian plates (Zonenshain *et al.* 1984; Puchkov 1997; Brown *et al.* 2002), resulting in W-E oriented compressional stress (Coward 1993; 1995). In the study area, inversion occurred along NNW-SSE to N-S trending faults such as the Keys Fault, Gogarth Fault, the western marginal fault of the East Deemster Basin and the Formby Point Fault System. Evidence for this is provided by the Carboniferous subcrop pattern presented by BGS (1994). The Pre-Permian subcrop inset in the marginalia of this map clearly shows erosion of Westphalian strata in NNW- to N-S trending belts associated with the hangingwalls of the Keys Fault (Fig. 5b), Gogarth Fault (Fig. 4a) and Lake District marginal faults (Fig. 5c). By contrast, Westphalian strata are well preserved on the footwall of these structures. The seismic data indicate the presence of N-S trending anticlinal folds cored by Namurian strata, dissected by faulting on their overturned limbs. Similar subcrop patterns, with Namurian subcrops in the cores of Variscan inversion anticlines e.g. the Murdoch Anticline, are observed in Quadrants 43 and 44 in the southern North Sea (Corfield *et al.* 1996), and indeed, the two basins exhibit a similar degree of inversion. At present the NNW-SSE to N-S trending faults are extensional structures of Permian and younger age; but these are here inferred to have initiated as thrusts or positive flower structures ('ancestral faults') on the overturned limb of the anticlines during Variscan inversion, as reported in the Ogham Inlier by Quirk & Kimbell (1997). A component of sinistral shear is likely from the observed relationship of the folds in the Ogham Inlier to the ancestral Keys Fault. Seismic mapping in the present study (Fig. 6) confirms the pre-Permian subcrop pattern presented by BGS (1994) and has identified a possible interference structure between the two trends in the Ribble Estuary Inlier. Although it is conceivable that inversion on faults with both WSW-ESE and NNW-SSE trends could have occurred in one Variscan phase of inversion, comparable to the partitioned deformation system advocated for the Northumberland Basin by De Paola *et al.* (2005), the above evidence would appear to suggest two, separate, nearly orthogonal phases of Variscan inversion are more likely. Extensional reactivation of the ancestral late Variscan structures in W-E extension during Permian to Mesozoic time, facilitated development of NNW-SSE to N-S trending graben of the EISB, strongly discordant to the strong SW-NE structural grain established by Caledonian compression, Mississippian extension and early Variscan inversion. Strong uplift and erosion during the Variscan inversion led to complete removal of the Pennine Coal Measures strata underlying the Lagman Basin. The ancestral Keys Fault played a key role in partitioning the former Eubonia Tilt-block into western and eastern segments, the latter being almost obliterated by post-Variscan events. Inversion on the same trend may have led to uplift and erosion of Carboniferous strata deposited within basins on the North Channel Basin complex.

Post-Variscan structural evolution

The post-Variscan structural evolution of the EISB has been thoroughly described in numerous previous publications (BGS 1994; Jackson *et al.* 1987; 1995; 1997; Jackson & Mulholland 1993). As a result, only a generalised account, focussing on those elements where the Palaeozoic structure has a bearing, will be presented here. Following the Variscan basin inversion and regional uplift described above, there is clear evidence on seismic profiles for the erosion of Pennine Coal Measures strata from the crests of inversion anticlines, and tectonic dissection of the latter adjacent to the Keys, Lagman, Lake District Boundary and Formby Point faults prior to deposition of Permian strata (BGS 1994). Jackson & Mulholland (1993; p793) and Jackson *et al.* (1997; Figure 2) recognised significant thickening of the Appleby Group (Lower Permian), possibly to as much as 1150 m (Jackson & Mulholland 1993), in a belt extending from the Berw

Basin to the Formby Oilfield. For example, the well 110/11-1 proved 763 m of Collyhurst Sandstone Formation (Appleby Group), while 110/7-2 12 km to the north proved only 40 m, and none is present in the vicinity of the Morecambe fields. The belt of thick Appleby Group strata directly overlies the Môn - Deemster Foldbelt, providing strong evidence for significant early Permian penecontemporaneous relief within, and deep erosion of, the tectonically weakened inversion belt. The area must have had a substantial topography in early Permian time. It is interesting to note that significant pre-Permian palaeotopography was described at Formby by Falcon & Kent (1960).

A series of NNW-SSE to N-S trending rifts began to develop in response to W-E extension affecting the crust of the Pangaea Supercontinent that was established during the Variscan Orogeny (Whittaker 1985; Coward 1995; Chadwick & Evans 1995). In the Worcester and Knowle basins onshore, rifting was able to exploit the N-S ('Malvernoid') grain previously established by late Precambrian orogeny (Pharaoh 1987; Barclay *et al.* 1997) and subsequent Variscan inversion (Chadwick 1993). The rifts propagated with stepwise, *en-echelon* offsets through the province, from the Stafford and Cheshire basins and EISB through the Portpatrick and Larne basins and the North Channel to the western Scottish offshore basins (Ziegler 1990). The Solway and Peel basins subsided less than the EISB, and are elongated SW-NE, reflecting structural control by the extensionally-reactivated Caledonide 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). By Triassic time, the EISB was a mature component of the Central European Basin System (Scheck-Wenderoth *et al.* 2007; Pharaoh *et al.* 2010), receiving up to 5km fill of Sherwood Sandstone Group clastic sedimentary rocks and Mercia Mudstone Group mudstones and evaporites (Jackson & Mulholland 1993). Small relict outliers of Lias (early Jurassic) strata in the Carlisle Basin (Warrington *et al.* 1997), Peel Basin (Chadwick *et al.* 2001) and EISB (Jackson & Mulholland 1993) indicate that subsidence continued into Jurassic time. Evidence for mid- 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 & Mulholland 1993; Quirk *et al.* 1999). 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 (Pharaoh *et al.* 2016b).

Opening of the Atlantic Ocean east of Greenland by Paleocene times associated with putative Icelandic Plume activity (e.g. Brodie & White 1994; Nadin & Kuznir 1995) resulted in voluminous magmatism in the Inner Hebrides and in N Ireland just to the west of the study area. The Fleetwood Dyke Complex (Kirton & Donato 1985) was intruded *en echelon* across the main graben of the EISB. Magmatic and thermal processes on a lithospheric scale resulted in regional thermal doming of the crust below the EISB (White 1988) in Palaeogene or possibly, late Cretaceous, time (Cope 1994, 1997). Across the study area, the combination of enhanced regional and local heat flow led to a further phase of hydrocarbon generation (Cowan *et al.* 1997; Meadows *et al*. 1997). Superimposed on the regional, thermal uplift described above were the effects of later crustal shortening, associated with the developing Alpine Orogeny in southern Europe. Apatite fission-track data indicate a second Cenozoic phase of 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 southern North Sea (Van Hoorn 1987; Badley *et al.* 1989; Chadwick 1993). 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 southern side of the 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 e.g. the Rhyl and Lennox fields (Haig *et al*. 1997), reflecting the 'buttressing' effect of the margins of the EISB (Pharaoh *et al.* 2016b). Throughout the EISB, seismic data indicate the presence of gentle Cenozoic inversion anticlines (Figs. 4a, b, c) superimposed on an earlier generation of Variscan inversion anticlines (Pharaoh *et al.* 2016a; b), the 'posthumous' tectonic style recognised by Jackson & Mulholland (1993). Further tightening of the Variscan inversion anticlines during Cenozoic (Alpine) crustal compression resulted in the development of more open structures in the Permo-Triassic cover. This was likely an important process in the generation of the traps in the Hamilton fields (posthumous upon the Môn-Deemster inversion belt) and the Millom, Dalton and Calder fields (posthumous on the Keys trend of latest Variscan inversion). The Cenozoic inversion history is thus complex, involving contractional reactivation of precursor normal faults, posthumous folding and regional arching and uplift of basin depocentres, upon which various thermal effects due to magmatic intrusion and possible underplating have been superimposed. A detailed treatment of these potential Cenozoic impacts upon the Palaeozoic hydrocarbon system is beyond the scope of this paper.

Petroleum systems of the Carboniferous basins of the EISB

In the EISB, a proven petroleum system is present, involving a Carboniferous source (Colter & Barr 1975; Cowan 1991; Stuart 1993; Armstrong *et al.* 1997), reservoirs of the Ormskirk Sandstone, locally the uppermost formation of the Triassic Sherwood Sandstone Group, and halite seals (Fig. 7). A substantial number of exploration wells have been drilled, but few penetrate the Permian and the potential pre-Permian resource underlying the EISB fields is poorly known. The North and South Morecambe gasfields (Fig. 6), with a combined in place recoverable of 5.2 tcf (Cowan 1996), were discovered in the 1970s and lie in large regional anticlines associated with rollover and salt-facilitated low angle detachment faulting, of Triassic to Jurassic age (Knipe *et al.* 1993). Further modification of trap geometry occurred in Miocene time as a result of Alpine inversion. An initial charge of hydrocarbons (probably mostly oil) in Jurassic time was originally thought to have been derived from Pennine Coal Measures source rocks, as in the southern North Sea (Bushell 1986). Subsequently the Bowland Shale Formation was confirmed as the source (Armstrong *et al.* 1997). This early charge was associated with the formation (at about 180 Ma) of a 'platy-illite' layer, interpreted as a palaeo-hydrocarbon-water contact (Bushell 1986; Woodward & Curtis 1987; Knipe *et al*. 1993), which was lost during the early Cretaceous and the present (mostly) gas charge is believed to result from a further cycle of hydrocarbon generation (also from the Bowland Shale Formation?) associated with an elevated geothermal gradient during the early Cenozoic (Cowan & Bradney 1997). Hydrocarbon migration continues in the basin to the present day, as witnessed by the seepage of oil into Quaternary sands and peats at Formby, on the Lancashire coast.

In the 1990s, the Hamilton, Douglas, and Lennox fields, with a mixture of oil and gas, were discovered parallel with the North Wales coast in the southern part of the EISB (Fig. 6). Most of the deep wells of these fields encountered Millstone Grit Group below the Variscan Unconformity, as at Formby. 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 (correlative of the Bowland Shale Formation) of NE Wales thereby proving the Bowland Shale source (Armstrong *et al.* 1997). 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 in North Wales (Falcon & Kent 1960). Waxy crude shows in the Millstone Grit Group in well 110/07b-6 (1510 m-1675 m; Released Geochemical Report) showed an isotopically similar source to shows in wells 110/07-2, 110/08-3 and Formby. The API of the Irish Sea oils range from 40-45 at Lennox and Douglas (Hardman *et al.* 1993), to 37 at Formby (Armstrong *et al.* 1997), perhaps suggesting a less mature source in the onshore field. Many additional small fields have been discovered subsequently, mostly in the centre of the EISB and mostly containing gas, culminating with the Rhyl discovery in 2009. In the Irish Sea, no significant Carboniferous reservoirs or good shows have been reported but there is at least one discovery (113/27-2) in the Collyhurst Sandstone (Appleby Group).

Stratigraphy of the petroleum system

Carboniferous source rocks are shown in Fig. 7, as covering the lower part of the Namurian and highest part of the Visean where shales are developed; Pennine Coal Measures may make a contribution where preserved. The lithostratigraphical terminology used here is that introduced by Waters et al. (2011) to better integrate the offshore with the onshore geology than previous schemes (e.g. Jackson *et al.* 1999). 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 groups. Above the Variscan Unconformity the Permian Appleby and Cumbrian Coast groups, and the lower, tight part of the Triassic Sherwood Sandstone Group, also intervene. A Pendleian time slice (Fig. 9) highlights the persistence of the relatively deep marine hemipelagic successions (Bowland Shale Formation) across the central part of the British Isles, including the Craven Basin, EISB and westward towards the Dublin Basin (Ramsbottom *et al.* 1969; Cope *et al.* 1992; Jackson & Mulholland 1993; Wakefield *et al*. 2016). 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 characterised by a thick pro-deltaic ramp turbidites, overlain by a siltstone-dominated slope succession, in turn overlain by a fluvio-deltaic, delta-top sandstone (Collinson 1988; Wakefield *et al.* 2016). The hemi-pelagic successions have gamma values which suggest potential as source rocks. The overlying successions of the Pennine Coal Measures and Millstone Grit groups have potential as a combined 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 and 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 (Fig. 6). Interpretation of well logs and associated core analyses (biostratigraphy, poroperm etc) frequently provide alternative stratigraphic interpretations to those shown on the well composite log, and have been carried out in this study (Fig. 9a, b). Many authors have referred to the problems in identification that results from 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 EISB. 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 (Fig. 9b). This is important because it shows the probable topography of the Carboniferous surface, deformed and uplifted by the Variscan Orogeny, and the extent of erosion and eventual burial. The Cumbrian Coast Group comprises a varied sequence of thin sandstones, anhydrites, limestones, halites and mudstones, mostly red in colour. Underlying redbeds have therefore been interpreted either as a mudstone facies of the Appleby or as Warwickshire Group strata, on well composite logs. The favoured interpretation, combining all the seismic and well evidence, is that the red beds directly underlying the Cumbian Coast Group 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.

Source rocks

One of the key risks in the Palaeozoic of the greater Irish Sea province is the quality, extent and maturity of source rock intervals. Potential source rocks include coals of the Pennine Coal Measures (Westphalian) and upper Millstone Grit (Namurian) groups; shales of the Bowland Shale Formation and Millstone Grit Group (Pendleian and Arnsbergian); and older Visean shales (unproven by sample data), for example in the lower part of the Yoredale Group. Compilation of the Rock-Eval source rock geochemical data from released legacy reports revealed a small data set (264 samples), limiting the analysis which could be undertaken (Vane *et al.* 2016). Where penetrated, the Pennine Lower Coal Measures Formation, Millstone Grit Group and Bowland Shale Formation are mainly gas-prone strata with poor-fair remaining generative potential, and are mature to the gas window at the sampled intervals in Quadrants 110 and 113 (Vane *et al. 2*016). Some shales within the Millstone Grit Group have TOC values (Fig. 11f) and S1 hydrocarbon values (Fig. 11a) greater than the Bowland Shale Formation. 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 to fair. 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 Total Organic Carbon (TOC) and low residual hydrocarbon generative potential. Data is generally lacking to characterise kerogen types using a Van Krevelen plot, however data from well 110/02b-10 (Fig. 11b) suggests a kerogen mix between Type II and III for the Millstone Grit Group and Pennine Coal Measures. A similar mixed system can also be expected for the Bowland Shale Formation but with a higher proportion of Type II kerogens. The high TOC and widespread extent of the Bowland Shale Formation favour it as the primary source rock, at least in the southern part of the Irish Sea. The other potential sources are ranked as secondary to this.

Hydrocarbon maturation and generation

Vitrinite reflectance data (Fig. 11d) shows that the Bowland Shale source rocks in wells are mature for oil and gas generation (Corcoran & Clayton 1999; Vane *et al.* 2016). EISB oils were considered to have been derived from the source in the range 0.75-0.85% Ro maturity, and the condensate from >1.0% Ro (Armstrong *et al.* 1997). Given the structural complexity for the area of interest, a singular burial trend and maturity profile cannot be defined. Cowan *et al.* (1999) gave examples of varying thermal and burial history at the basin margins changing over tens of kilometres. Three wells show a correlation of maturity increase with depth within the T_{max} dataset: 110/07b-6, 110/02b-10 and to a lesser extent 113/27-1, indicating 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 or possibly due to T_{max} suppression caused by variable kerogen and free oil composition (Fig. 11c). Onshore Isle of Man boreholes (Shellag, Ballavarkish, Black Marble Quarry; Fig, 5) show a similar range of T_{max}, albeit with few samples (Racey 1999).

Basin modelling

A lack of preserved post-Jurassic strata has resulted in a range of burial and thermal models for the EISB, for example Cenozoic uplift estimates ranging from <1 km to up to 3 km (Cowan *et al.* 1999; Quirk *et al.* 1999 and references therein). In this study, well 110/07b-6 was chosen for burial and thermal modelling as it had the most complete geochemical profile and thick Carboniferous section (Gent 2016; Fig. 12). The well is situated on a minor Variscan structural high, and is considered reasonably representative of the more marginal areas of the basin. The burial model was matched to the measured vitrinite reflectance (VR) profile and the calculated VR profile (from T_{max}) (Fig. 12). Using published studies (Cowan *et al*. 1999; Quirk *et al.* 1999) and seismo-tectonic interpretations from this study a 700 m uplift event in the late Carboniferous, followed by a minor 150 m uplift during development of the Late Cimmerian Unconformity, and a final 1100 m uplift and increase in palaeo-heatflow in the Cenozoic were included. The modelling shows that burial of the Bowland Shale Formation source rock in the Carboniferous resulted in the early-mid mature oil window being reached, before uplift and subsequent deeper burial in the early Cenozoic, just reaching main gas generation in the base of the drilled strata (Fig. 12). This is consistent with the oil shows documented in the well geochemical report (Geochem Laboratories Ltd 1988). Carboniferous trap formation, migration and generation were all likely to have occurred during the Variscan Orogeny. However, subsequent uplift would have almost certainly breached the traps. Migration and trap formation was renewed in the Mesozoic and Cenozoic, with any modern day hydrocarbon accumulations required to have survived the potential structural breach as a result of Cenozoic inversion.

Migration

Migration of hydrocarbons into Triassic reservoirs and traps has clearly been successful as evidenced by the producing oil and gas fields of the EISB. Oil migration to the Triassic Hamilton fields may have occurred, vertically along faults, in Jurassic and Cretaceous times (Yaliz 1998; Haig *et al.* 1997; Yaliz & Taylor 2003). This study has highlighted how these fields overlie the Môn-Deemster inversion belt described above (Fig. 6), the structures of which may have acted as first stage reservoirs, subsequently breached to allow migration into overlying Triassic traps, formed posthumously as late as Cenozoic time, on a template created by the Variscan inversion structures. In a similar way, the Millom, Dalton and Calder fields, lying close to the Keys Fault, and Lennox Field, close to the Formby Point Fault, are Cenozoic age traps formed posthumously on a template provided by the second phase of Variscan inversion structures. 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 within the dismembered Eubonia Tilt-block 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 a conceptual Carboniferous petroleum system model, 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. In the north the boundary is strongly faulted (Lagman, Eubonia and Lake District boundary faults).

Characteristics of potential reservoirs

A reservoir evaluation of Permian and Carboniferous intervals, designed as a quick-look regional overview, was based on legacy core plug-measured porosity and permeability data and continuous petrophysical interpretations for 8 wells (Hannis 2016). Net-to-gross, porosity and basic permeability estimates were calculated for each formation, summarised in Table 1. In general, the results illustrate fairly low net to gross values of less than 10% (except in the Permian-aged Appleby Group where net-to-gross was 79%), porosities (highest formation averages mostly around 10% but up to 19 % in the Appleby Group) and mainly poor average permeabilities (highest formation averages mostly less than 10 mD). Further examination of the distribution of potentially higher permeabilities within the Millstone Grit sandstone intervals could be worthwhile (Table 1). The core plug measured porosity versus permeability data by formation is exhibited in Fig. 13.

The aeolian-dominated Permian Appleby Group strata that include the Collyhurst Sandstone are a prospective reservoir interval. The group as proven in well data 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). Based on 6 wells in Quadrant 110 in the depth range 1300-2400 m, maximum measured core porosity is 21% with a highest formation average in all wells of 13%. Permeability is however poor, with a maximum measured permeability of 71.5 mD (vertical, k_v), and a highest formation average of 0.8 mD (horizontal, k_h) and 7.90 mD (vertically). Petrophysical analysis has confirmed the group as being a sandstone-dominated interval with an average net-to-gross ratio of 79%. Petrophysical 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 (Table 1 and Hannis 2016).

The Warwickshire Group is the equivalent of the Ketch and Boulton formations of the southern North Sea in Quadrant 53 and Quadrants 43-44 (Waters *et al.* 2011). Onshore, the Warwickshire Group of North Wales and Cheshire Basin comprises predominantly red, brown, purple-grey mudstones and sandstones and locally green-grey siltstones and mudstones with thin coals. However, potential reservoir sandstones can be locally significant. The amount of sandstone relative to mudstone and siltstones within constituent formations of the Warwickshire Group varies considerably. In West Cumbria, 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). The Halesowen Formation was productive in the small mined Coalport Tar Tunnel ‘field’ in Shropshire during the 18th and early 19th century (Smith *et al.* 2005). In the East Midlands, the Warwickshire Group has been documented to have better reservoir characteristics than productive older late

Carboniferous strata, but was spatially confined to the synclines (BGS 1984; Pharaoh *et al.* 2011). 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. Therefore investigation of the Warwickshire Group as a reservoir interval offshore was considered, though seismic mapping indicated a limited extent in the greater Irish Sea province (Fig. 6) and there are no well penetrations and therefore no reservoir data for the group. However, Bolsovian-Asturian (Westphalian C-D) age strata are recorded in well 33/22-1 along strike in the Kish Bank Basin (Jenner 1981).

In the EISB, the Pennine Coal Measures Group comprises interbedded grey mudstone, siltstone and pale grey sandstone, commonly with mudstones containing marine fossils in the lower part of the lower and upper part of the middle subdivisions, and more numerous and thicker coal seams in the intervening interval. The group shows an overall blocky to erratic log response, with thick high gamma mudstone and siltstone intervals and relatively thin (3-15 m) low gamma sandstones. The sandstones show considerable variation in wireline log character, including 'boxcar' motifs in thick, distributary channel sandstones (Wakefield *et al.* 2016). Onshore, sandstones are also 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). Based on five wells in Quadrants 110 and 113, in the depth range 1400-3050 m, maximum measured core porosity is 10% with a highest formation average in all wells of 6%. Permeability is generally poor with a maximum measured horizontal permeability (k_h) of 9.43 mD, and a highest formation average for k_h of 1.07 mD. Petrophysical analysis of the Pennine Coal Measures Group provides a similar outlook, with an average net to gross of 9%. Net intervals have reasonable porosities, with the highest average porosity at 11%. Permeability is generally poor with the highest average permeability estimated at 0.8 mD. However, permeability up to 61 mD was estimated in one well (110/02b-9; Table 1, Hannis 2016).

The Namurian-aged Millstone Grit Group comprises cyclic sequences of quartzo-feldspathic sandstone, grey mudstone, thin coal and prominent seatearths, resulting from deposition by repeated progradational deltas (Collinson 1988). Common marine bands are present and represent discrete flooding events (Waters & Condon 2012). 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 thick) occupy incised valleys (Waters & Condon 2012; Wakefield *et al.* 2016). Jackson *et al.* (1997; Figure 6) identified a Kinderscoutian sandstone unit up to 90 m thick in the Liverpool Bay region (111/20-1), which can be correlated with wells farther north (112/30-1 and 113/27-2) although considerably reduced in thickness. Onshore, Millstone Grit sandstones are encountered in NE Wales (e.g. Cefn-y-Fedw, Gwespyr Sandstone, Aqueduct Grit), 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 to SW under the Cheshire Basin (Collinson *et al.* 1977; Smith *et al.* 1995). This pattern continues into the offshore of the EISB with Namurian absent at the Rhuddlan well on the North Wales coast (Figs. 5, 9b). Based on samples from four wells in Quadrants 110 and 113, at 1950-3550 m depth, maximum measured core porosity is 10 % with a highest formation average in all wells of 6% (Table 1). Permeability is poor, the maximum measured was 0.37 mD (k_h), and the highest formation averages for k_h and k_v were 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 10 %. Net intervals have a reasonable porosity, the highest average porosity is 11 %. Permeability is poor with an average estimate of 0.2-2.1 mD, apart from one well 113/27-2, which shows an average of 367.7 mD (Table 1). Further analysis of these sandstones could therefore be beneficial (Hannis 2016).

The Bowland Shale Formation is only examined in the wells 110/11-1 and 110/07b-6, 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 may be present. Well 110/07b-6 encounters a total of 16 m of these sandstones, giving a net-to-gross of 3%. (The other well examined, 113/27-2, contained no net intervals). No core samples were taken, but petrophysical interpretation revealed that the net intervals had porosities up to 23%, although the average porosity was 7 %. Permeability estimates appear poor with an average of 0.7 mD and maximum of 16.2 mD (Table 1, Hannis 2016).

Carboniferous Limestone Supergroup sequences are interpreted to be widespread over the EISB and thus worthy of investigation as a reservoir. Petrophysical analysis of the limestones encountered in two wells (112/25a-1 and 111/25A-1) appear clean, but have too low matrix porosities (less than 5 %) to be considered as a reservoir (Table 1), but accumulations could be hosted in secondary porosity as a result of karstfication or fracturing. Onshore, the Hardstoft Oilfield in Derbyshire (Craig *et al.* 2013) 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 & Kent 1960). Karstified limestones such as those known from Anglesey (Walkden & Davies 1983) and apron reefs like those which crop out at Castleton, Derbyshire might be present in the offshore. Seismic evidence for the possible presence of reefs towards the top of the ramp of the Eubonia Tilt-block in Quadrant 109 (Fig. 4a) was described above and indicated schematically in Fig. 4a. Waulsortian mud-mounds 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 in the Craven Basin. In the prolific Williston Basin of Canada, collapsed mud-mounds up to 100 m tall provide excellent porosity but were initially hard to identify on seismic data (Kupecz *et al.* 1996).

Seal rocks

The Cumbrian Coast Group, which includes the Manchester Marls (Fig. 7), provides the most extensive potential seal to Permian or Carboniferous rocks across the whole of the greater Irish Sea area. The unit consists of thick evaporites in the north and central East Irish Sea, thinning southward, passing laterally into dolomitic mudstones (Jackson & Mulholland 1993; Wakefield *et al.* 2016), and is encountered in wells in surrounding sub-basins. This seal has been proven to trap hydrocarbons in the well 113/27-2, and sealing potential is proven in 112/25a-1, with minor gas shows in the tight Appleby Group. In the producing EISB fields, any Cumbrian Coast Group seals were breached as 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), various fields in the Silver Pit and Cleaver Bank basins of the southern North Sea and numerous fields in the Netherlands and Germany (Pletsch *et al.* 2010), and could be expected to work in Carboniferous basins of the Irish Sea.

Hydrocarbon prospectivity of the Carboniferous basins outside the EISB

Whilst basins of the greater Irish Sea province outside the EISB have extensive seismic coverage of variable quality, there are few wells. Data is therefore lacking to constrain their hydrocarbon systems and is heavily dependent on onshore analogues.

Solway Basin

The Permian – Jurassic Solway Basin, linked NE to the Carlisle Basin and SW to the Peel Basin is underlain by a Carboniferous basin of the same trend, an extension of the Northumberland Trough (Chadwick *et al.* 1995; Fig. 2). 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 (Fig. 7). The Yoredale Group sandstones, limestones and siltstones represent a fluviodeltaic depositional environment (see Wakefield *et al.* 2016) which is a northward lateral equivalent of the basinal Bowland Shale Formation, i.e. the Bowland Shale facies is not proven and may not be present. The presence of delta-top lacustrine facies is a possibility, but has not been demonstrated. In the onshore Cumberland Coalfield, the coals are gassy (Colter 1997), but the Pennine Coal Measures Group have not been penetrated offshore in the Solway Basin. Potential Carboniferous reservoir intervals include a relatively small area of

Warwickshire Group on both sides of the Maryport Fault (Figs. 5a, 6) and the Fell Sandstone Formation in the main part of the basin.

Peel Basin

The Peel Basin is a Permian-Jurassic basin lying between the Isle of Man and Northern Ireland, underlain by a Carboniferous carbonate platform. Wells 111/25a-1 and 111/15-1 penetrated the Mississippian age Carboniferous Limestone Supergroup, in contrast to the time-equivalent 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 being present in younger strata between 111/25a-1 and the Isle of Man coast, but there is no data to test this hypothesis. The seismic reflection data are generally of poor quality, but allow the presence of a small outlier of Namurian strata to NW of the Isle of Man. The Peel Basin may extend to the Carlingford Lough area near the Irish border, south of the Mourne Mountains (Fig. 2). BGS boreholes (in Quadrant 112, near the Irish coast) 73/65 and 73/67 are of probable Visean age and form a rim to the Lower Palaeozoic Longford-Down Massif. BGS borehole 71/43 near the Isle of Man coast was dated as Namurian. The data available preclude evidence of a working Palaeozoic petroleum system in the Peel Basin, a conclusion previously reached by both Newman (1999) and Quirk *et al*. (1999).

North Channel Basin

The North Channel Basin is a NW-trending Permo-Triassic basin complex lying between the Southern Uplands and the Longford-Down Massif of N Ireland (Quinn 2008) and forms the main rift through the massif. Two tilt-blocks, the E-dipping Portpatrick and W-dipping Larne sub-basins, recognised by Maddox *et al.* (1997), are separated by the Southern Upland Fault (Fig. 2). Several smaller basins lie parallel in Scotland (Stranraer, Lochmaben) and Ireland (Strangford Lough). In the Portpatrick Sub-basin, the underlying strata are possibly Devonian, although the seismic is poorly resolved because the only well (111/15-1) passed through a fault adjacent to the Southern Uplands, and did not prove a Carboniferous section. Data is lacking for the presence of source, reservoir and seal in this area (Maddox *et al.* 1997). Permo-Triassic and underlying Devonian and Carboniferous strata are present onshore in the Larne and Lough Neagh basins of N Ireland. Onshore in the Midland Valley of Scotland and in N 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; Read *et al.* 2002; Underhill *et al.* 2008; Reay 2004; 2012). Onshore in N Ireland, a Carboniferous prospect was drilled by Infrastrata plc in Woodburn Forest in 2016, without success (website). Seismic interpretation offshore (Pharaoh *et al.* 2016a) has included a Carboniferous succession in the Larne Basin buried to 5000 m and with faulting and folding observed offering potential for structural traps. However the interpretation is poorly constrained by data, precluding detailed assessment of petroleum system elements.

Brief mention can be made of the Rathlin Trough, which lies outside the study area, and for which only limited seismic data, covering the offshore extension of the Machrihanish Coalfield, have been studied. The source rocks include coals and oil shales (Murlough Bay Formation) of early 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 (Read *et al.* 2002). Drilling took place at Magilligan in the west of the basin and at Ballinlea in 2008. In the latter well, oil was produced from the Carrickmore Formation sandstones (Providence 2013) of the wide Visean subcrop (Smith 1985).

Petroleum system knowns and risks

The distribution of the principal Carboniferous source rock (Bowland Shale Formation) as inferred from the seismic interpretation is constrained by a few borehole penetrations in the EISB, 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 time-equivalent Yoredale facies is therefore poorly known. The lack of any offshore well data requires analogy with the adjacent onshore Carboniferous. In the northern part of the EISB, the very deep burial of the source (now at >7 km depth despite Cenozoic inversion) and the strong thermal impact from the Fleetwood Dyke means it is probably overmature, compatible with high CO_2 and Nitrogen levels observed in Rhyl and neighbouring fields (Cowan, 1996; Centrica, *pers. comm.* 2015). Leakage of hydrocarbons in the Cenozoic following fault reactivation and degassing consequent upon regional uplift, are further risks throughout the region. 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 beneath the Peel Basin. Attenuation of the Carboniferous sequence southwards towards the Welsh Massif (Fig. 4b, 9a) 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. Similarly, the reservoir porosity-permeability characteristics are poorly known over large parts of the region studied. The petrophysical analyses presented here suggest that the Carboniferous sandstones beneath the Morecambe fields have very poor porosity and permeability, confirming information provided by Centrica (*pers. comm.* 2015). This is no doubt a consequence of their deep burial, and processes such as platy-illite development and silica cementation which severely affect even the overlying Triassic formations (Colter 1989; Bushell 1986; Woodward & Curtis 1987; Cowan 1991; Stuart 1993). The Carboniferous tight gas play may work if hydraulic fracturing can be applied, as is presently being attempted at Kirby Misperton (Cleveland Basin) and in the Ravenspurn Deep (southern North Sea). Extensive carbonate platforms surrounding the Isle of Man (Manx Platform) and off North Wales (Colwyn Platform) also have unknown poroperm characteristics. Until more is known about possible secondary porosity (following dedolomitisation) and fracture density, the reservoir properties of these areas are ranked as high risk.

The Mercia Mudstone Group is a proven caprock to Sherwood reservoirs and is present throughout the EISB but is absent across the margins of the basin complex. The potential seal of the Permian Cumbrian Coast Group sequence thins and fails in the same directions. In the EISB a relatively thick shale and evaporite (St Bees Evaporites, Cumbrian Coast Group) may be developed. The same is true in the Portpatrick and Larne basins, where several Triassic halites are present (Quirk *et al.* 1999; Quinn 2008).

Analysis of seismic data, integrated with well, core data etc, indicates that the marginal areas of the EISB hold the greatest potential for undiscovered hydrocarbon resources in the Carboniferous, although the geochemical, petrophysical and other essential data are scant. In general, the presence of an effective seal is considered to represent the biggest risk in the hydrocarbon system at the margins of the EISB. Yet-to-find prospects are anticipated to be relatively small in volume and with shallow column heights supported by Carboniferous intra-formational seals. The most prospective parts of the region, outside the Triassic play, are considered to be:

- Thick Westphalian combined reservoir and source rock sequences preserved in the Eubonia Tilt-block in Quadrant 109 (Fig. 4a), located outside the main Permian-Mesozoic graben system and less affected 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 (the Môn-Deemster Foldbelt; Fig. 4b) correlated with structures on the Formby Platform, and the onshore Ribbledale Foldbelt, from which hydrocarbons sourced by a thick Bowland Shale sequence have leaked into the overlying, Triassic-hosted Hamilton fields (block 110/13). The biggest risk here is whether reservoirs exist and remain unbreached at the pre-Permian level, and retain good poro-perm 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 (Fig. 4a), in Asbian reefal facies with enhanced secondary porosity. Here, source rock presence and migration pathways, reservoir properties and seal quality are major risks.

- The Ribble Estuary Inlier east of the Formby Point Fault (Figs. 5c, 6) may contain a working petroleum play. It lies adjacent to the deep Deemster Basin where there is a thick sequence of Upper Carboniferous sedimentary rocks preserved, and between the Formby and Lennox fields. Well 110/9-1, within the Deemster Basin was dry, but appears to have good porosity in the Ormskirk Sandstone though no shows. Fluorescence was recorded in the Appleby Group.

- A potential play exists sourced from the Bowland Shale Formation in the deep Godred Croven Basin drilled by 110/11-1 migrated into the Carboniferous reservoir 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.

Discussion

The pre-Permian structural synthesis presented here is speculative in view of the limited number of offshore well penetrations of Carboniferous strata. For example, further tectonic partitions may exist within the inferred Eubonia Tilt-block. It is possible, for example, that the eastern part of the structure (underlying the Keys and Tynwald basins of the EISB) may represent a separate tilt-block with a hinge in the Lake District Boundary Fault System, and a master controlling fault in the west (ancestral Keys system). The presence of such a basin, referred to as the Lancaster Fells Basin, was inferred by Cowan *et al.* (1999). However, the available evidence suggests that the NNW structural trend did not play a significant role until latest Carboniferous time, so that an ancestral Keys Fault is regarded an unlikely Visean structural element. The nature of the link between the structures of Quadrant 109 and onshore Lancashire has been much speculated on in the past (e.g. Ramsbottom *et al.* 1978). Jackson & Mulholland (1993) recognised the Menai Strait-Pendle Line link, but preferred to link the Q109 Arch to the High Haume Anticline of the Furness Inlier, in the southern Lake District. This paper shows that the Ribblesdale Foldbelt does extend west of the Leyland Basin and Formby Point Fault (c.f. Jackson & Mulholland 1993; Figure 4 and p797) and links to the Q109 Arch, via the Môn-Deemster Foldbelt. More detailed seismic mapping of the Upper Carboniferous interval will be required to elucidate what is probably an intricately folded subcrop pattern here. We support the proposed continuity of the Bowland Basin southwestwards into the offshore area, as inferred by Corfield *et al*. (1996) and Cowan *et al*. (1999). From the perspective of hydrocarbon prospectivity, the presence of the prolific Bowland Shale Formation source rock interpreted across much of the EISB has been a key element in the hydrocarbon system of the overlying Permian to Mesozoic basins. Prospective reservoir intervals with moderate porosity are likely to exist in the Warwickshire Group and Pennine Coal Measures Group in the marginal parts of the EISB, although the permeability is likely to be poor. The EISB lay to west (Fig. 8) of the main Pennine deltaic and fluviatile fairway in the onshore (Fraser *et al.* 1990), and consequently shows a lower net/gross sand ratio. Evidence from geophysical logs indicates that the EISB was less influenced by the repeated deltaic incursion so evident onshore, and a sharp transition between deltaic and basinal shale facies, of the type seen at Mam Tor and Edale, is neither observed nor to be expected there.

In a review of the deep reflection seismic data for the Irish Sea, principally BIRPS' WINCH lines and some deep data from JEBCO, England & Soper (1997) state that from this limited dataset, there is no clear evidence for reactivation of earlier structures during either Carboniferous sedimentation or Variscan inversion. Using the exploration seismic data, this study describes the presence of fold-thrust structures in the pre-Carboniferous basement and, in the Môn-Deemster Foldbelt, demonstrates their role in controlling both Carboniferous extensional and inversion structures. The interpretation presented supports the view of England & Soper (op. cit.) that the faults controlling Permian and Mesozoic basin development are discordant to the Caledonian, Acadian and early Carboniferous structural grain (as exemplified by the Q109 structures), and are therefore juvenile structures developed in late Westphalian to early Stephanian time. Evidence presented here suggests that these were initiated as a result of a late phase of Variscan inversion, reflecting W-E Uralide compression, superimposed on an earlier phase produced by N-S compression. The timing of these two inversion phases is imprecisely defined in the Irish Sea due to the significant missing stratigraphic section. However, in late Variscide intramontane basins in central France, N-S compression in Stephanian B time is followed by inferred phases of compression on NW-SE (late Stephanian B) and W-E (mid-Stephanian C) principal stress axes (Gélard *et al.* 1986), the 'Bourbonnaise Phase' of Grolier (1971). Although interpreted in terms of systematic rotation of the principal horizontal compressive stress axis (Gélard *et al.* 1986; Blès *et al.* 1989; Ziegler 1990), Faure (1995) considered these deformations a consequence of late Variscan orogenic collapse. In the UK region, other manifestations of the late W-E compressive phase may include the W-E oriented basaltic dykes, and a component of growth of N-S trending folds, within the Midland Valley of Scotland (Monaghan & Pringle 2004; Timmerman 2004); and W-E directed transport of fold nappes on the eastern margin of the Worcester Graben (Peace & Besly, 1997).

The observed variation in Variscan structural orientation in the Variscan Foreland of Britain is currently explained in terms either of one resolved compressional vector (Corfield *et al.* 1996), or of strain-partitioning across a heterogeneous basement template (e.g. De Paola *et al.* 2005). In the Irish Sea, it is difficult to argue for a strong control by a N-S oriented basement grain, as identified, for example, within the Midlands Microcraton (Corfield *et al.* 1996), and the presence of two discrete late Variscan deformation phases is regarded as a more likely scenario. Another expression of the multiple inversion history, and very significant for the formation of Ormskirk traps in the cover, is the impact of posthumous folding. This process, first recognised and described by Suess (1904), is very clearly demonstrated in the Irish Sea, where a template of Variscan inversion anticlines in the Carboniferous sequence underlies structures with similar trend but lower amplitude in the Permo-Triassic cover.

Conclusions

The study has demonstrated that the basins of the Irish Sea preserve a Phanerozoic geological history as complex as that of the UK onshore. A strong SW-NE structural grain was imprinted on the crust during late Precambrian and Caledonian accretion and orogenic deformation. Dipping zones of strong reflectivity in seismic sections are interpreted as major thrusts and shear zones, some of which can be correlated with known examples onshore. Mississippian rifting on SW-NE trending faults resulted in depocentres which accumulated marine shale source rocks, preceding regional thermal subsidence. The Eubonia Tilt-block is a major Carboniferous syndepositional element beneath the northern part of the EISB, but was partially dismembered by the formation of the ancestral Keys Fault system. The Eubonia-Lagman fault system formed the syndepositional bounding fault to the tilt-block. The Bowland Shale Formation forms the main source rock interval, with inferred thickest development likely within the Môn-Deemster Foldbelt, the offshore correlative of the Bowland Basin, and its inversion, the Ribblesdale Foldbelt. This source rock is buried to depths >7 km under the Lagman and Keys basins and is probably post-mature there at the present day.

The Millstone Grit Group and Bowland Shale Formation contain thin clean sandstones locally up to 90 m thick which could be considered potential reservoirs. Prospective areas at these stratigraphic levels may exist at depth adjacent to the Keys Basin, and west of the Keys Fault. The Millstone Grit Group also has the potential to act as a secondary source rock, as do the Pennine Coal Measures Group when buried deep enough to achieve maturity. However, the latter were stripped from a large area of the EISB following Variscan inversion. Pennsylvanian strata exhibit marked thinning to the south onto the Conwy Platform. Burial by Upper Carboniferous sediments likely resulted in early maturation of kerogen in source rocks within the deepest basins, but destruction of reservoir porosity and permeability in the depocentres.

Warwickshire Group sedimentary rocks were not so deeply buried, and are likely to retain better reservoir characteristics.

The Variscan Orogeny, in late Carboniferous time, caused uplift, folding and thrusting on both WSW-ENE (Môn-Deemster) and NNW-SSE to N-S (Keys-Gogarth) trends, probably in two phases, corresponding to well-documented main compressional phases of the Variscan-Uralian Orogen. The later inversion phase occurred on NNW-SSE to N-S trending zones of deformation which would subsequently become localised as the main synsedimentary bounding faults of the EISB in Permian to Mesozoic time. Corfield *et al*. (1996) provided a definition of inversion intensity. In the greater Irish Sea region, the intensity ranges from moderate (in the EISB, Solway and Clyde basins) to strong, with almost complete removal of the post-rift fill (in the North Channel basins and Peel Basin). The timing of these events is poorly constrained in the Irish Sea due to significant missing stratigraphic section, but by comparison with intramontane basins in France, is likely of intra-Stephanian age. The Variscan inversion structures have not yet been adequately tested as targets. They form both first-stage hydrocarbon reservoirs and the structural template for more gentle, 'posthumous' folds produced by Alpine inversion which form traps in the Triassic cover (e.g. the Hamilton fields). Deposition of Permian Appleby Group and Cumbrian Coast Group strata resulted in a potential reservoir - seal combination overlying the Carboniferous source rocks. Permian to Mesozoic rifting is along NNW-SSE and N-S trends. These faults cut discordantly across the early Carboniferous structures and have allowed late Cretaceous to early Cenozoic vertical migration of Carboniferous-sourced hydrocarbons into Triassic reservoirs. There is a migration route to Triassic reservoirs in the centre of the EISB because the Warwickshire Group and Appleby Group strata have been removed from that area, and the thin Cumbrian Coast Group seal breached, where the producing hydrocarbon fields are located. The Clyde-North Channel basin complex, Solway and Peel basins also contain Devonian and/or Carboniferous rocks beneath Permo-Triassic strata, but have likely been buried less deeply than those in the EISB. The North Channel basins may also have suffered significant Variscan inversion. Extensive 2D seismic datasets cover the latter areas but there are only four well penetrations. There have been no discoveries, interpreted to be largely a consequence of the absence of a regional seal comparable in quality to the Mercia Mudstone Group in the EISB. The prolific Bowland Shale source is also absent in these basins, being replaced by fluvio-deltaic sedimentation of the Yoredale Group. Very limited well penetrations do not presently allow a realistic assessment of the prospectivity of the Carboniferous strata underlying these poorly drilled basins.

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Figure captions

Fig. 1. Key data evaluated during the study (2D seismic, black; 3D seismic outline, orange; wells proving Carboniferous strata, black dot; wells used in the petrophysical study, black square).

Fig. 2. Key Mississippian structural elements of the greater Irish Sea province. Incorporates information from Maddox *et al.* (1997), Parnell (1997) and Shelton (1997). Location of Permo-Triassic basinal features, following Jackson & Mulholland (1993) and BGS (1994), for reference purposes, in red: BB, Berw Basin; CP, Conwy Platform; DP, Deemster Platform; EB, Eubonia Basin; ED, East Deemster Basin; GB, Gogarth Basin; GC, Godred Croven Basin; KB, Keys Basin; LB, Lagman Basin; MF, Manx-Furness Ridge; NC, North Channel Basin; OP, Ogham Platform; PB, Peel Basin; Q109S, Quadrant 109 Syncline; SB, Solway Basin; TB, Tynwald Basin; WD, West Deemster Basin. Location of sections depicted in later figures: red line, seismic profiles (Fig. 3); green line, synoptic diagrams (Figs. 4, 5); black line, well transects (Fig. 9).

Fig. 3. Seismic reflection data. Locations are shown in Figs. 2 and 6. N.B. vertical scales in s TWTT.

a. Migrated seismic reflection line NW-SE across Quadrant 109: JEBCO JS-MANX-138. Includes content supplied by IHS Global Limited. Copyright © IHS Global Limited (2016). All rights reserved. Note the considerable thickness of Carboniferous strata in the Eubonia Tilt-block, here exceeding 2.5 s TWTT; brighter reflectivity towards top of tilt-block below Intra-Visean unconformity, possibly reflecting reefal development; and in the south, a northward-vergent anticline-thrust inversion couple, defining the northern edge of the Môn-Deemster Basin. The presence of Warwickshire Group strata is inferred from seismostratigraphic principles and has not yet been confirmed by drilling.

b. Arbitrary NNW-SSE line through the migrated 3D TerraCube® dataset, supplied courtesy of CGG GeoSpec. Note the presence of a series of inversion anticlines (Môn-Deemster Foldbelt) in the Carboniferous sequence, associated with thrusts (fault-plane reflections) which penetrate into the Caledonian basement. A less steeply dipping detachment is present at depth. The Bowland Shale Formation is inferred to occupy a rather transparent zone, sandwiched between more reflective Carboniferous Limestone Group (below) and Millstone Grit Group (above). The mildly deviated well 110/07b-6 proved 450 m of Bowland Shale Formation before terminating in strata of Pendleian age (unbottomed). Westphalian strata have been almost completely eroded following strong inversion during the earliest Variscan phase. Inversion anticlines of this generation were reactivated ‘posthumously’ by further compression during the Alpine Orogeny in Miocene time, producing more gentle anticlines in the Permo-Triassic cover, including the traps in the Ormskirk Sandstone Formation (Top SSG pick) hosting the Conwy, Douglas and other fields.

Fig. 4. Synoptic diagrams (‘cartoons’) to illustrate principal elements of the hydrocarbon system of the greater Irish Sea province. Locations are shown in Figs. 2 and 6. N.B. vertical scales in s TWTT. The basin names used are principally those of the Permo-Triassic EISB and contemporary basins (Jackson & Mulholland, 1993; BGS, 1994), rather than those of the Carboniferous elements newly named here:

a. Principal elements of the hydrocarbon system in the Eubonia Basin and Q109 Arch. Transect is parallel to Fig. 3a and father east, into the Eubonia Basin.

b. Principal elements of the EISB from the Lagman Fault (north) to the Welsh margin (south). The northern part crosses from the Ogham Platform, to the Lagman and Keys basins, where Westphalian strata are almost completely removed, the West Deemster Basin and Deemster Platform. Note thickening of the Bowland Shale Formation beneath Deemster Platform, associated with the offshore extension of the Bowland Basin. The southern part crosses the Môn-Deemster Foldbelt and is virtually colinear with Fig. 3b.

c. Principal elements of the hydrocarbon system in the Peel Basin. Note that fault displacements appear to be largely of post-Permian age, indicating little if any syn-depositional thickening across the Visean carbonate platform. Post-Visean strata were only preserved on the Manx margin.

Fig. 5. Synoptic diagrams ('cartoons') to illustrate principal elements of the hydrocarbon system of the greater Irish Sea province. Locations are shown in Figs. 2 and 6. N.B. vertical scales in s TWTT. The basin names used are principally those of the Permo-Triassic EISB and contemporary basins (Jackson & Mulholland, 1993; BGS, 1994), rather than those of the Carboniferous elements newly named here:

a. Principal elements of the hydrocarbon system in the eastern part of the Solway Firth Basin. Note the preservation of late Westphalian Warwickshire Group (Whitehaven Sandstone Formation) in the Cumbrian Coalfield adjacent to the Maryport Fault, and the axis of Alpine inversion significantly offset from the Variscan one. The Visean strata here are Border Group and Yoredale facies, with uncertain source potential.

b. Principal elements of the hydrocarbon system in the northern part of the EISB. The WSW-ENE transect crosses Variscan second phase inversion structures obliquely in the Ogham Inlier, western Keys Basin and the Cumbrian margin.

c. Principal elements of the hydrocarbon system in the southern part of the EISB. The W-E transect is located parallel to the southern edge of the Môn-Deemster Foldbelt, crossing some of the Variscan first inversion phase structures obliquely. N-S trending inversion structures of the second Variscan phase at the margins of the East Deemster Basin and on the Formby Platform are crossed obliquely. Note the excision of Westphalian strata on these inversion systems. Modified from Yaliz (1997; Figure 4).

Fig.6. Pre-Permian subcrop map showing key Variscan inversion structures (after Pharaoh *et al*. 2016b). Variscan inversion structures in Ogham Platform after Quirk & Kimbell (1997). Abbreviated structure names: DP, Deemster Platform; EDB, East Deemster Western Boundary Fault; FPF, Formby Point Fault; OP, Ogham Platform; RE, Ribble Estuary Inlier. Location of sections depicted in other figures: red line, seismic profiles (Fig. 3); green line, synoptic diagrams (Figs. 4, 5); black line, well transects (Fig. 9). Hydrocarbon fields from OGA website:
http://data.ogauthority.opendata.arcgis.com/datasets/

Fig.7. Petroleum system elements in a north-south transect across the central part of the region

Fig.8. Pendleian palaeogeography showing the Bowland Shale source rock distribution and lateral variation with Millstone Grit facies (from Wakefield *et al*. 2016).

Fig. 9. Well transects (from Wakefield *et al*. 2016). Locations are shown in Figs. 2 and 6. a. N-S transect across the EISB from the Lagman Basin to Rhuddlan, onshore North Wales. Note the truncation of the Warwickshire Group north of Point of Ayr and condensation of the underlying Westphalian strata, southward onto the Cambrian margin. Also note the variation in the thickness of the Appleby Group. b. W-E transect across the centre of the EISB from 109/5-1 in the Eubonia Basin to Roosecote, onshore north Cumbria.

Fig.10. Seismic structure map in depth (metres sub-sea level) for the Intra-Namurian pick, equated with the base of the Millstone Grit Group. For location of abbreviated Permo-Triassic basinal features (for reference purposes), refer to key to Figure 2.

Fig.11. A summary of the available geochemical data for Bowland Shale Formation lithologies in well 110/07b-6 and 110/02b-10. Data sourced from released legacy reports. Note that no Oxygen Index data are available for well 110/07b-6, so the data in the Pseudo-Van Krevelen Plot (Figure 11b) is from well 110/02b-10 (Millstone Grit and Pennine Coal Measures groups).

Fig.12. Modelled burial history for 110/07b- 6 showing that the Bowland Shale source rock entered the main gas generation window in the late Cretaceous-early Cenozoic. The well terminates within the Bowland Shale Formation.

Fig.13. Cross plot of core porosity and permeability for East Irish Sea Basin samples. For key to abbreviations see Table 1, except for: PLC, Pennine Lower Coal Measures; PMCM, Pennine Middle Coal Measures; WAWK, Warwickshire Group.

Table 1. Synthesis of petrophysical results by formation (from Hannis, 2016). NTG = Net reservoir thickness to gross formation thickness. Porosity and net-to-gross are expressed as a fraction. Minimum porosity in the log-derived porosity range is 0.05, the net reservoir porosity cut-off value. Permeability figures are in mD. Core porosity and permeability data are synthesised from legacy reports.

From: EIS_Summary_Petrophysics_final.xlsx in 21CXRM_IrishSea_PoropermPetropl

		Log der			
Stratigraphic unit name	**Code**	**Net thickness (m)**	**NTG**	**Highest Average Porosity**	**Porosity range**
Cumbrian Coast Group	CCO	81	0.07	0.14	0.05-0.43
Appleby Group	APY	936	0.79	0.19	0.05-0.40
Pennine Coal Measures Group	PCM	62	0.09	0.11	0.05-0.26
Millstone Grit Group	MG	293	0.10	0.11	0.05-0.31
Yoredale Group	YORE	16	0.02	0.07	0.05-0.30
Bowland Shale Formation	BSG	16	0.03	0.07	0.05-0.23
Carboniferous Limestone Supergroup	CL	0	0.00	0.05	0.05-0.05

ived			Core measured			
Highest Average Permeability estimate	Permeability estimate range	*Metres of log*	Highest Average Porosity	Porosity range	Highest Average	
					horizontal (kh)	vertical (kv)
0.17	0.02-1.39	*1197*	0.04	0.02-0.07	3.06	
6.89	0.17-82.27	*1191*	0.13	0.05-0.21	0.80	7.90
0.79	0.02-61.45	*795*	0.06	0.01-0.10	1.07	0.01
367.74	0.17-10000	*2971*	0.06	0-0.10	0.04	0.05
		783	0.01	0.00	0.00	0.00
0.75	0.15-16.19	*551*				
		246				

Permeability estimate		Samples	Comments
horizontal (kh)	vertical (kv)		
0.01-15.20		*6*	
0.00-1.72	0.17-71.5	*154*	Highest net to gross, highest porosity. Highest permeabilities values in the 50-100 mD range for several wells.
0.00-9.43	0.01-0.13	*55*	Low NTG (although third highest of the units examined). Reasonable average porosity. Permeabilities appear low. (Highest values of 61.4 mD in 1 well, but with no core data over that interval).
0.00-0.37	0.00-0.13	*49*	Highest permeability (although estimated with low confidence: seen in only 1 of 3 wells (113/27-2), with a relatively poor core-log data fit). Low NTG (although second highest of the units examined).
0.00	0.00	*9*	
		0	
		0	Matrix porosities are less than 5% therefore the unit is not considered to have any 'net' using the cut offs applied.

Figure 1

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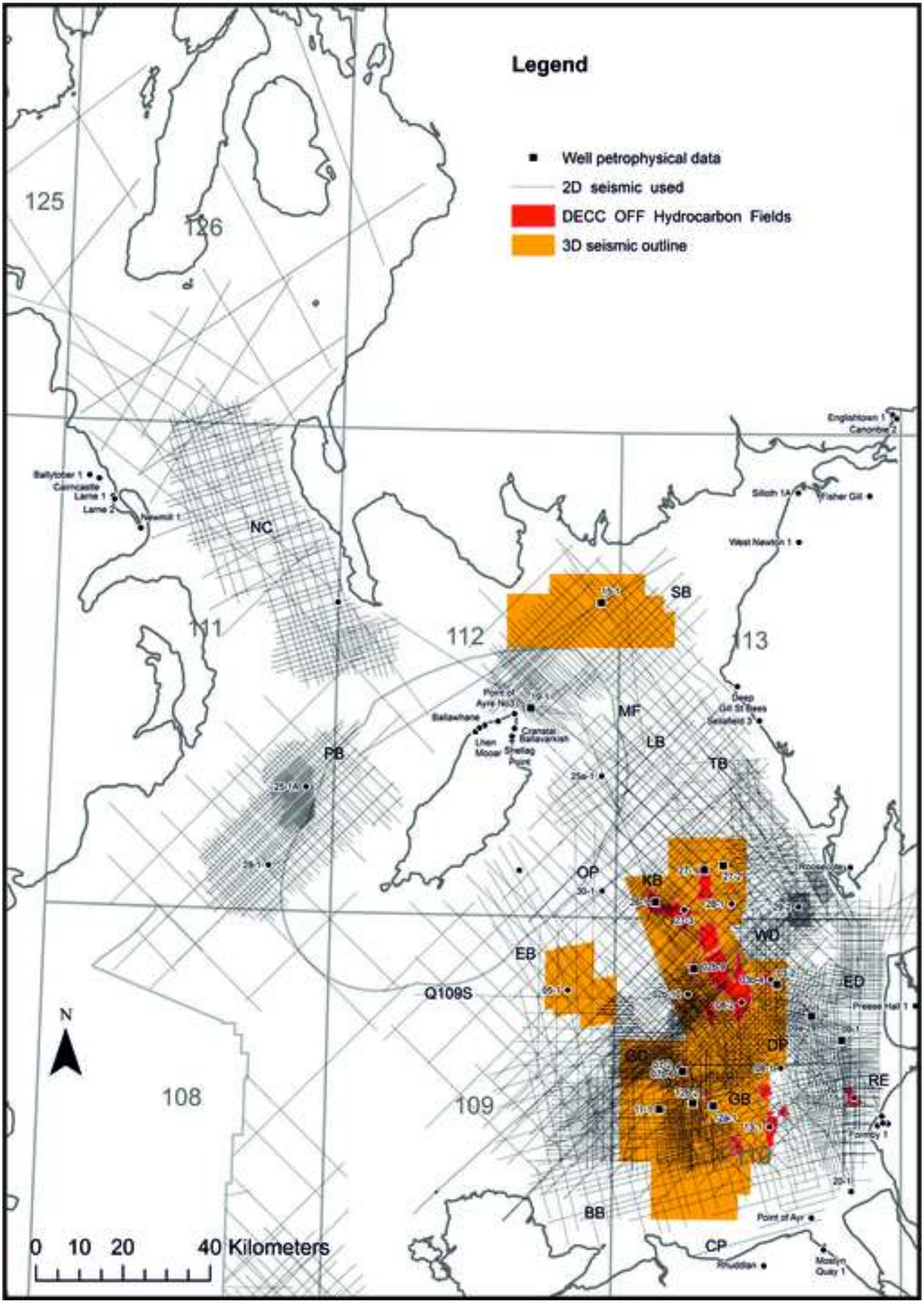

Figure 2

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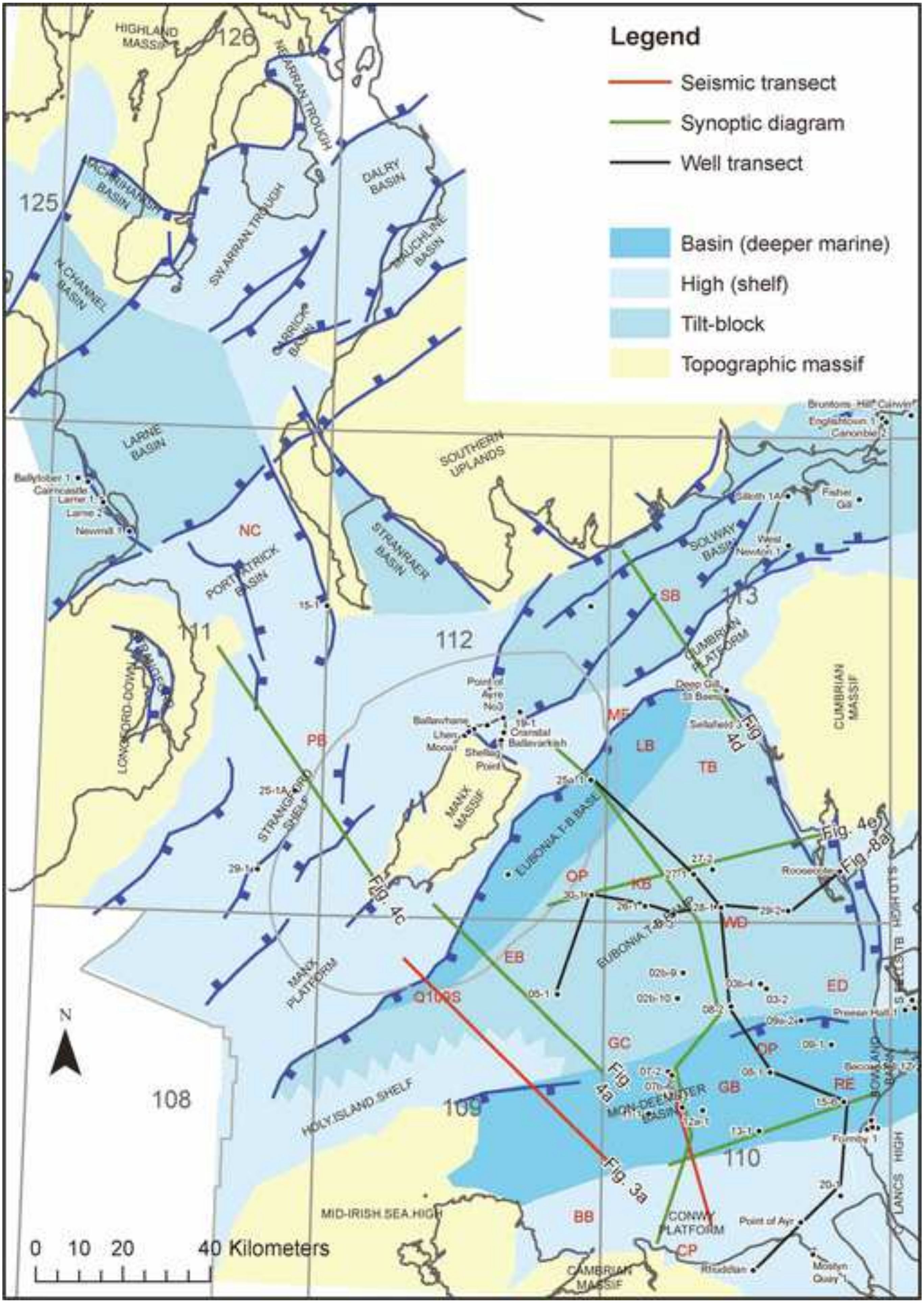

Figure 3

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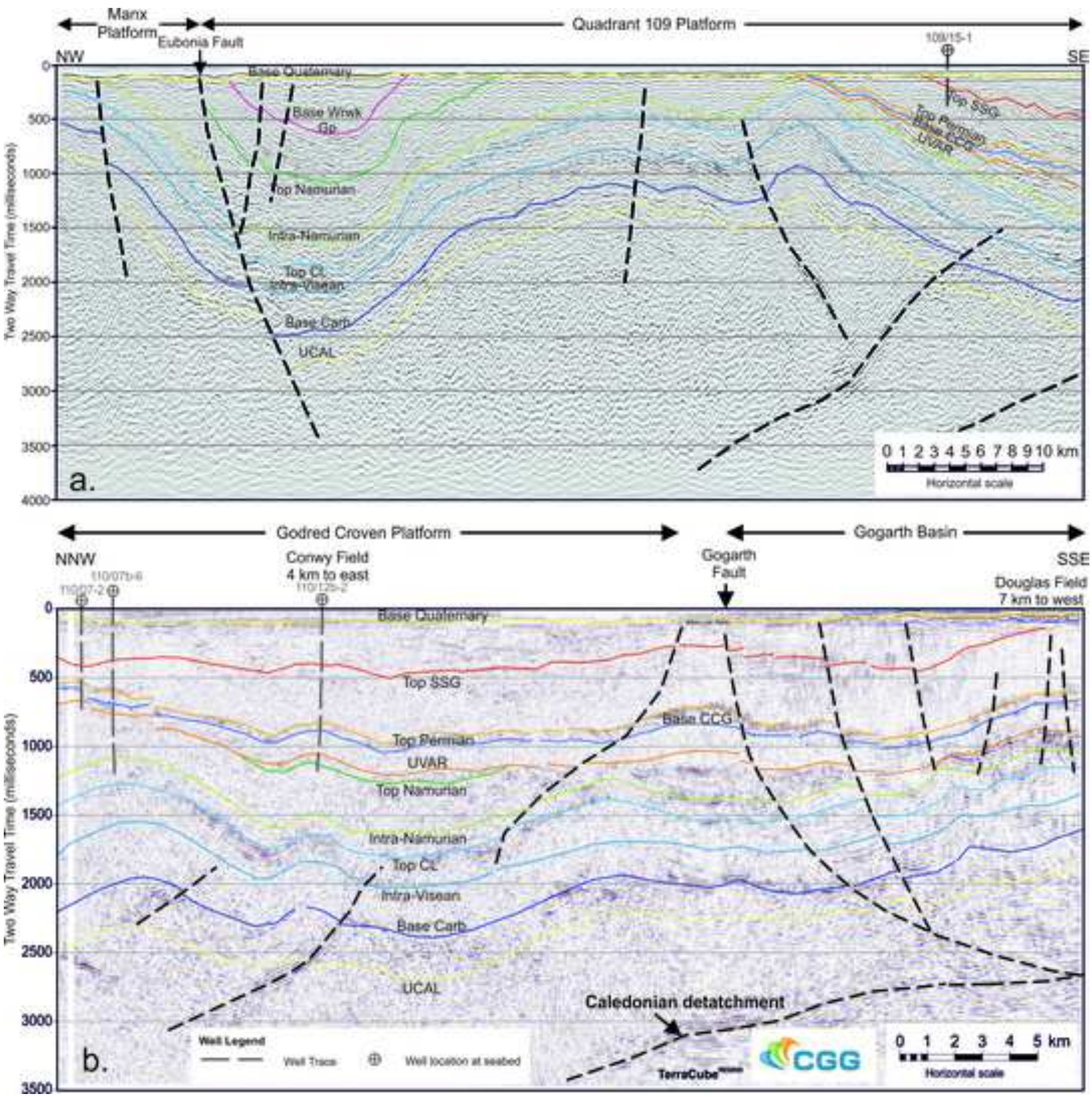

Figure 4a Click here to download Figure Fig4a.jpg

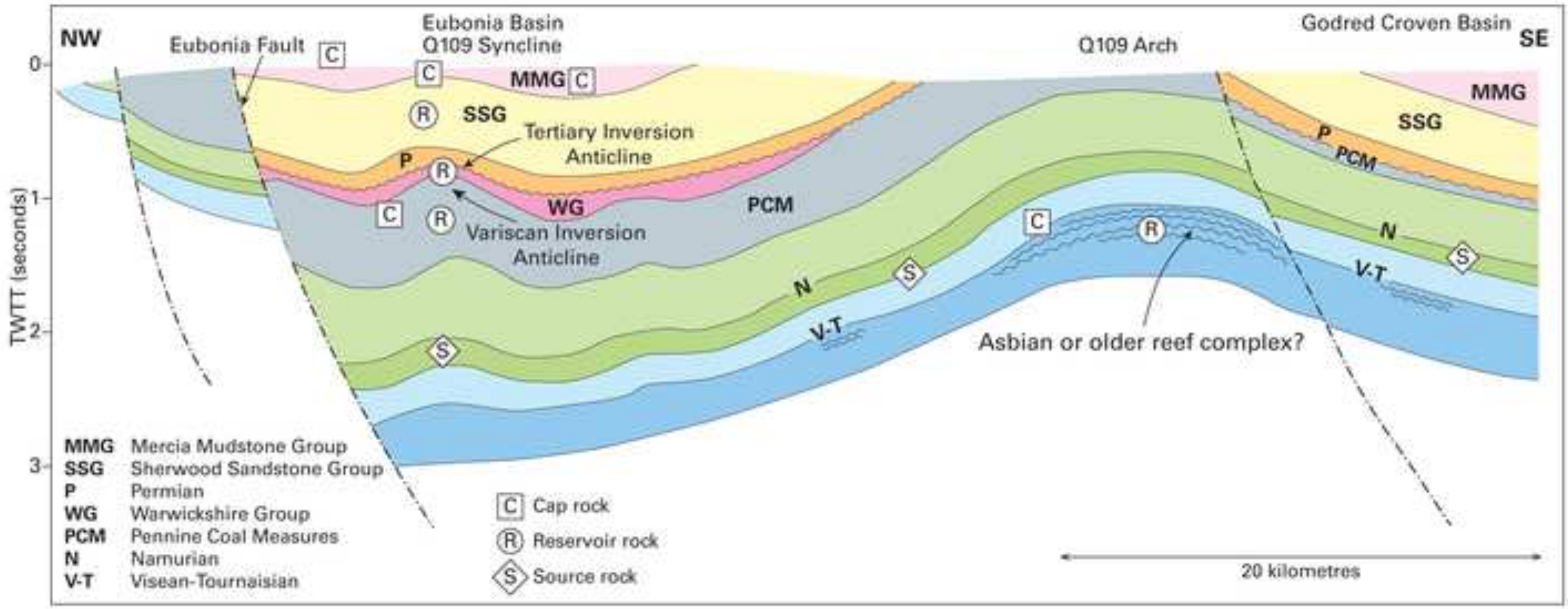

Figure 4b

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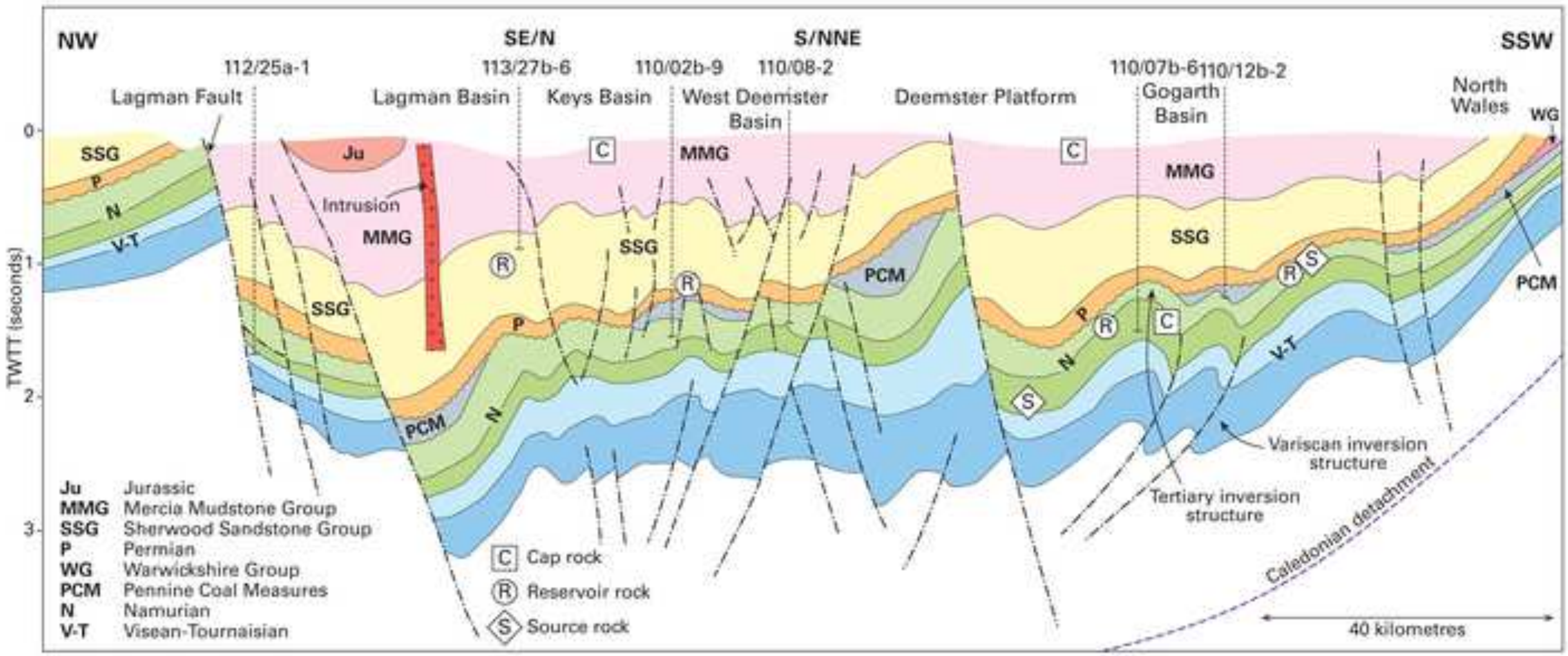

Figure 4c

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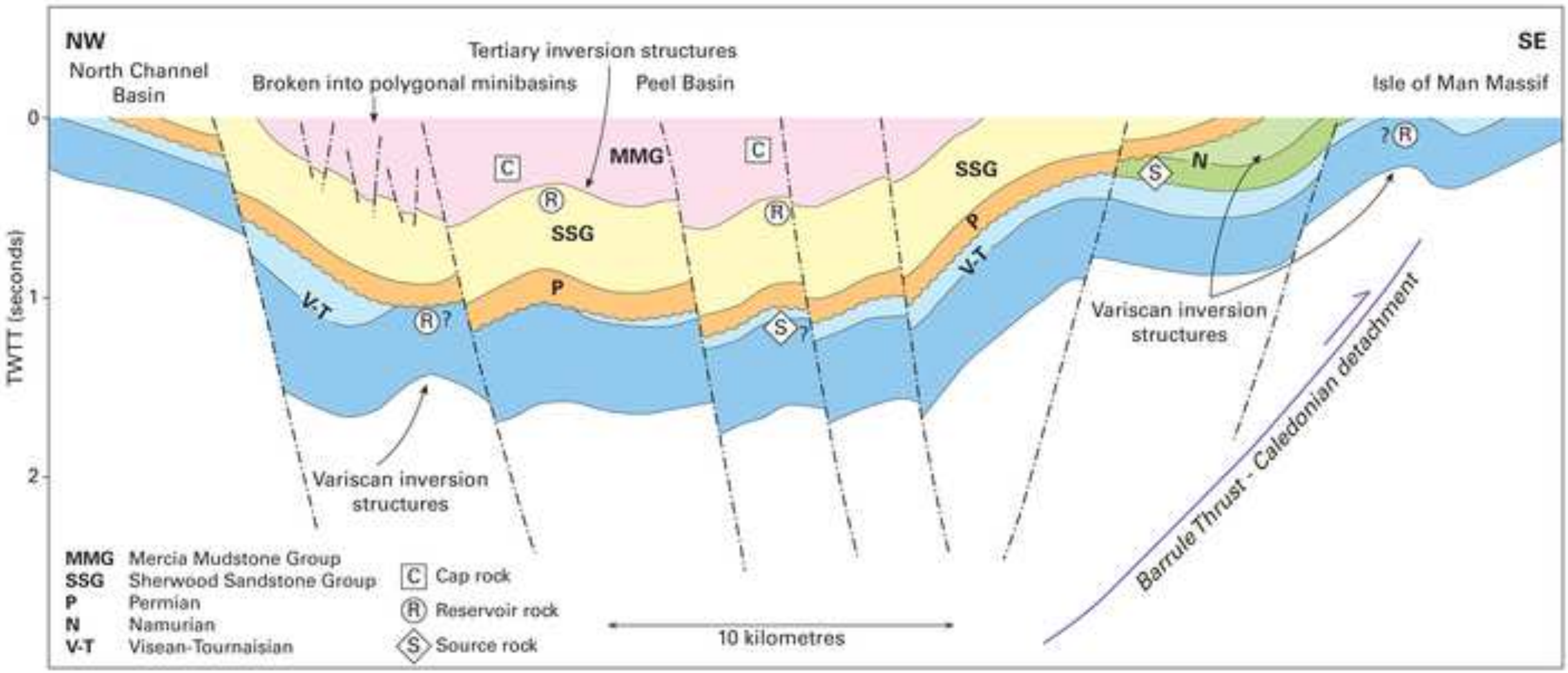

Figure 5a

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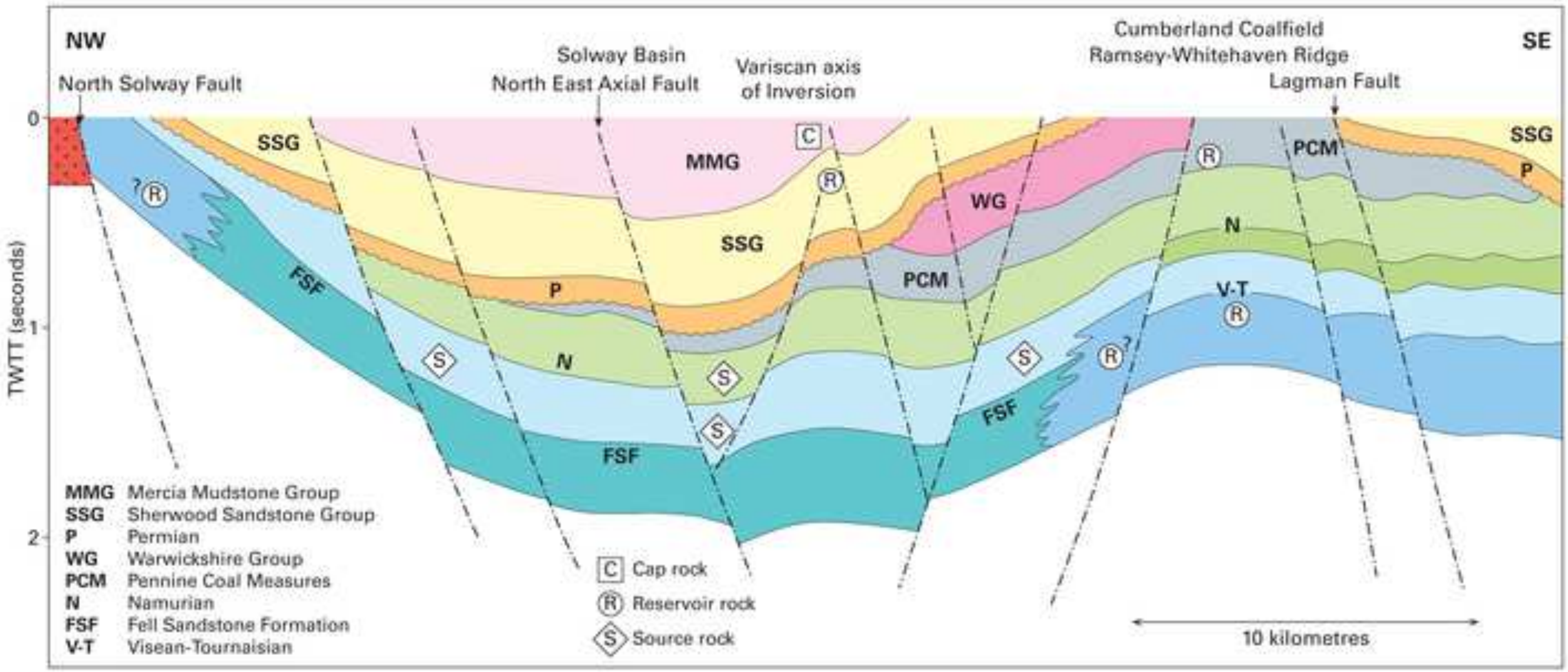

Figure 5b

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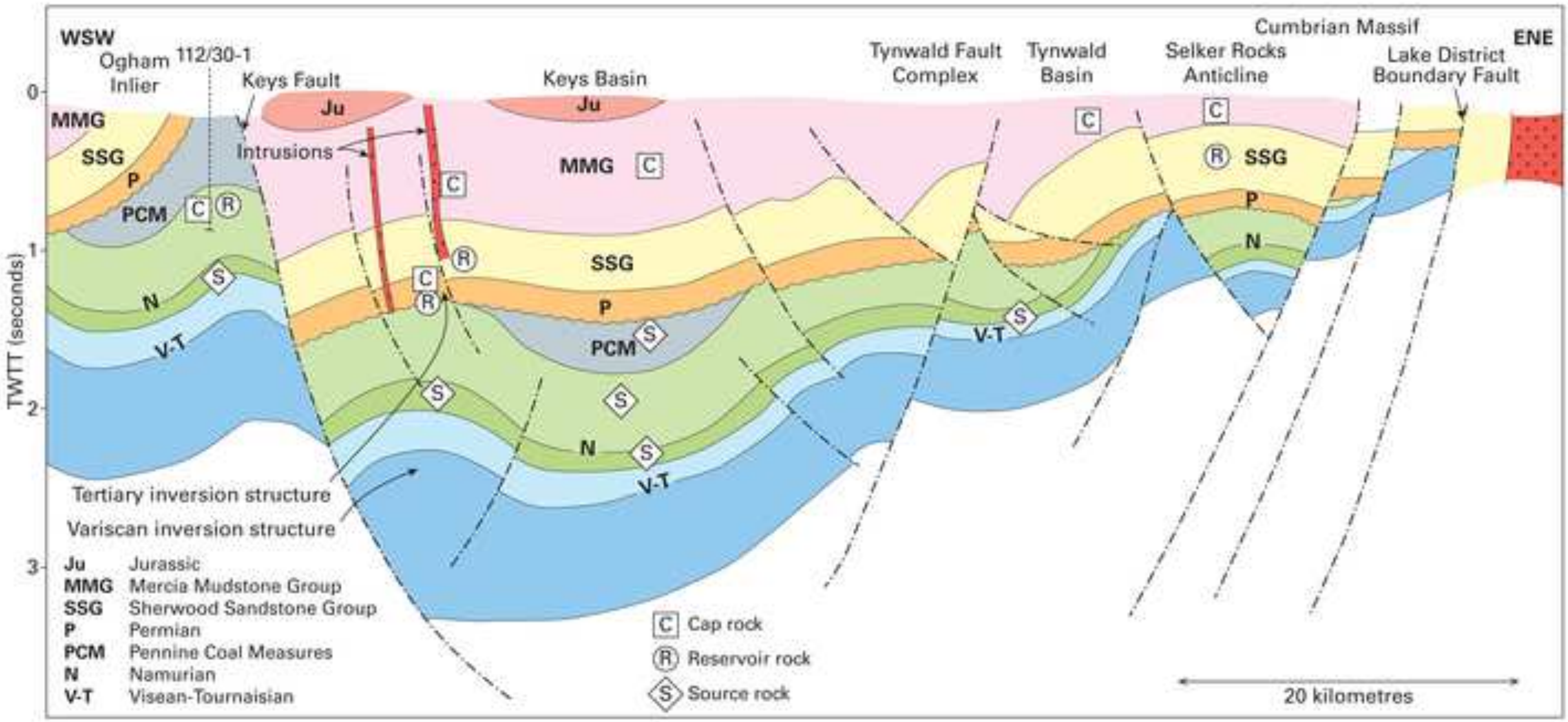

Figure 5c

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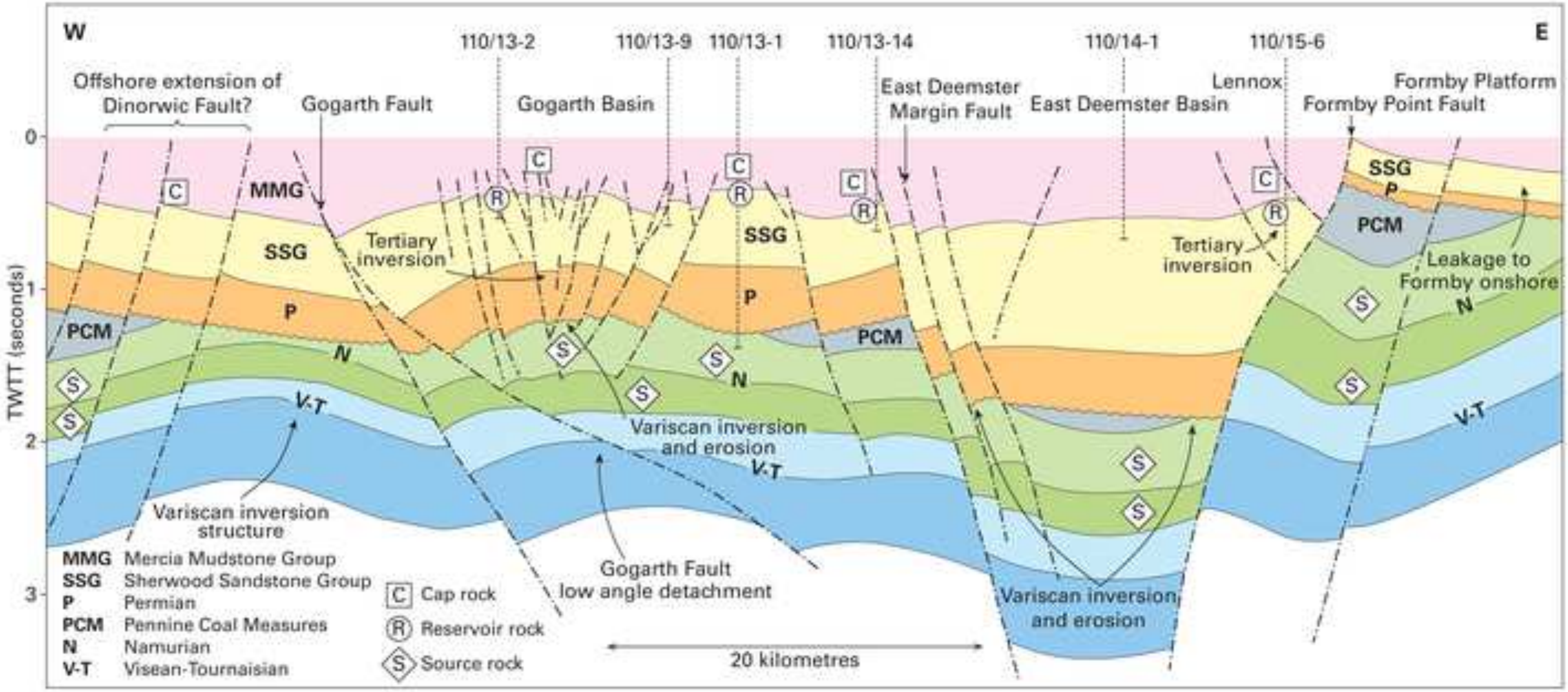

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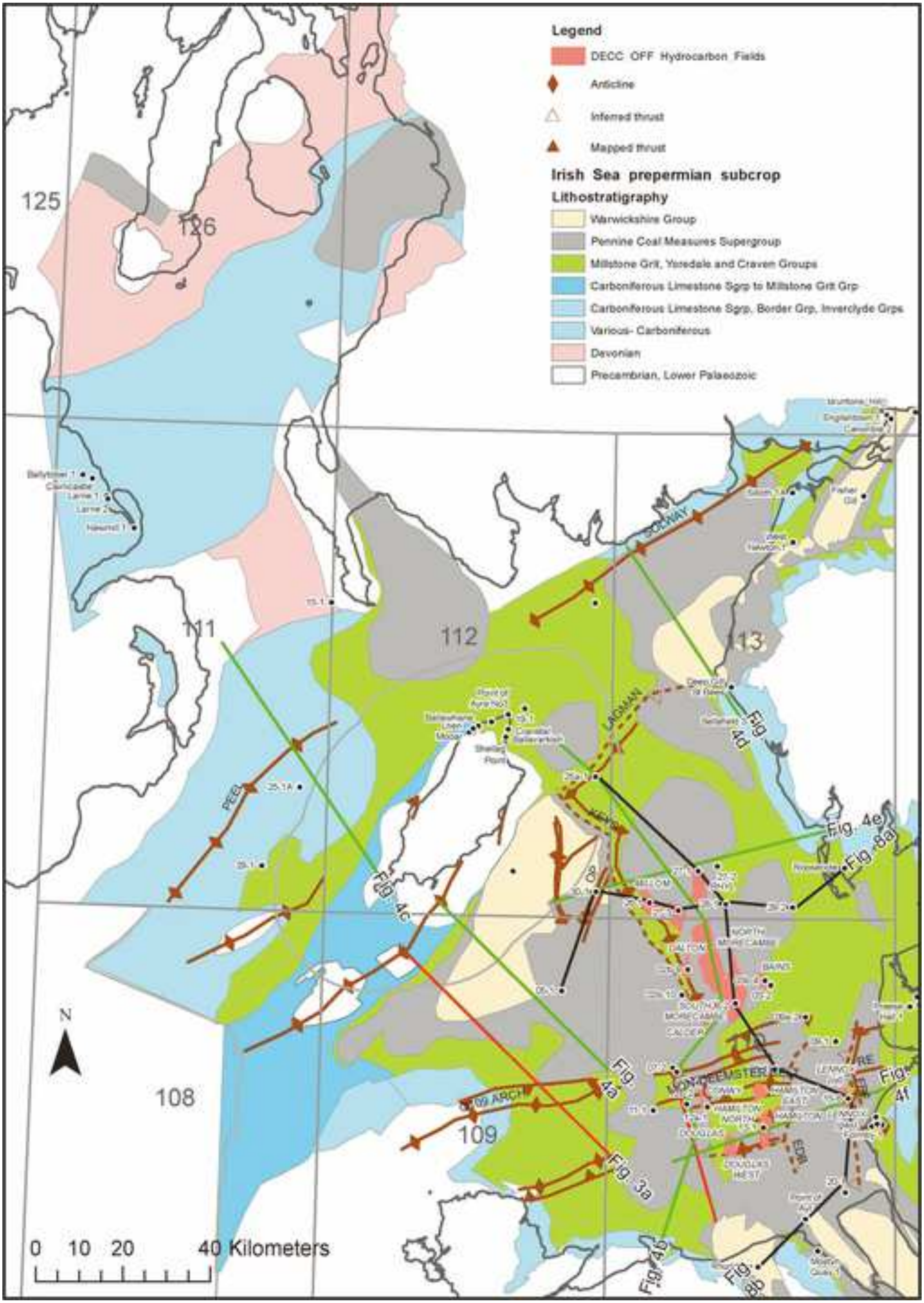
Legend
DECC OFF Hydrocarbon Fields
Anticline
Inferred thrust
Mapped thrust
Irish Sea prepermian subcrop
Lithostratigraphy
Warwickshire Group
Pennine Coal Measures Supergroup
Millstone Grit, Yoredale and Craven Groups
Carboniferous Limestone Sgrp to Millstone Grit Grp
Carboniferous Limestone Sgrp, Border Grp, Inverclyde Grps
Various- Carboniferous
Devonian
Precambrian, Lower Palaeozoic
125
126
111
112
113
108
109
SOLWAY
PEEL
LAGMAN
KEYS
109 ARCH
MORECAMBE
DEEMSTER
NORTH MORECAMBE
SOUTH MORECAMBE
DALTON
CALDER
BAIRD
HAMILTON NORTH
HAMILTON EAST
HAMILTON
DOUGLAS
DOUGLAS WEST
LENNOX
Fig. 4c
Fig. 4d
Fig. 4e
Fig. 8a
Fig. 4a
Fig. 4b
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Fig. 8b
Fig. 4f
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0 10 20 40 Kilometers

Figure 7

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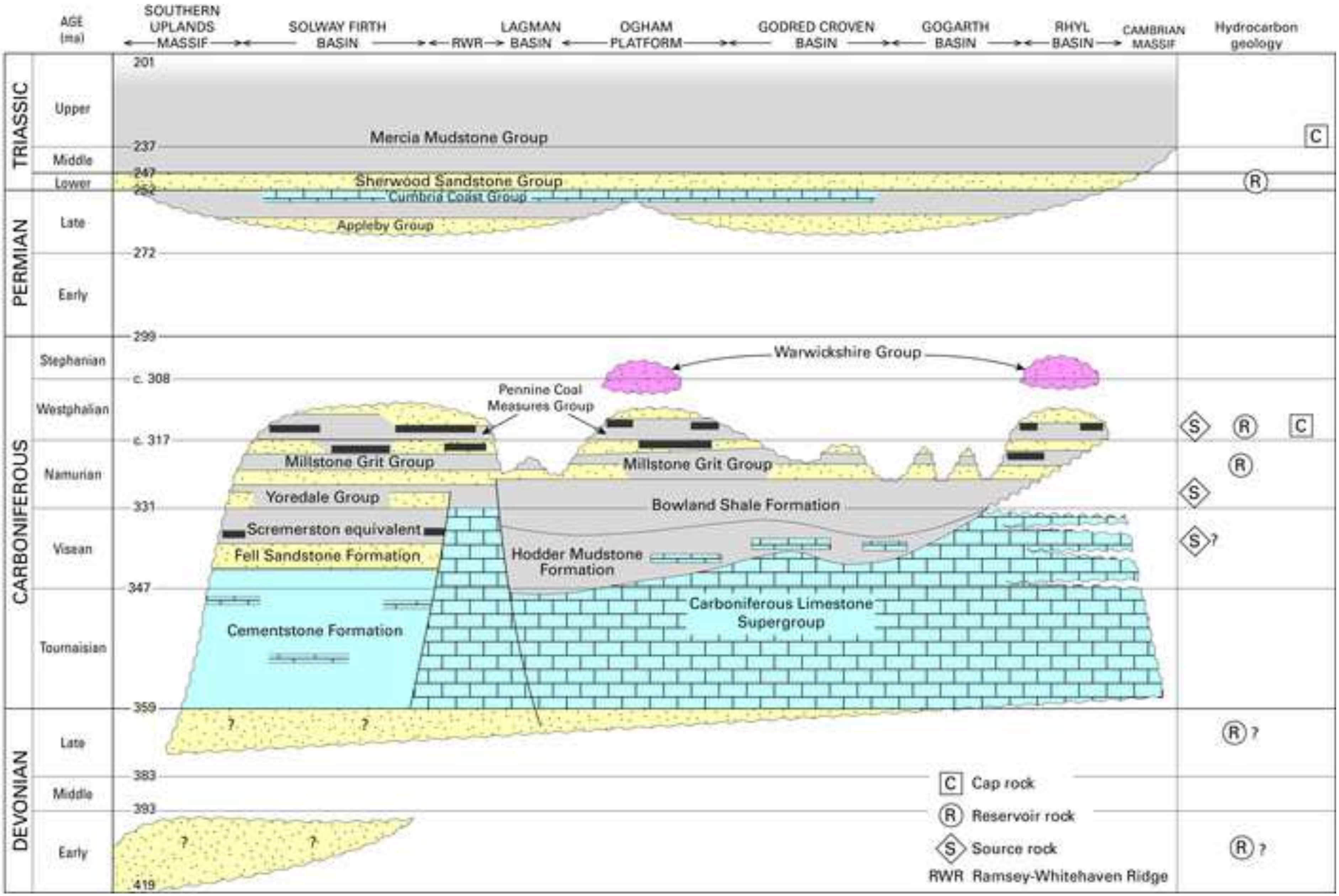

Figure 8

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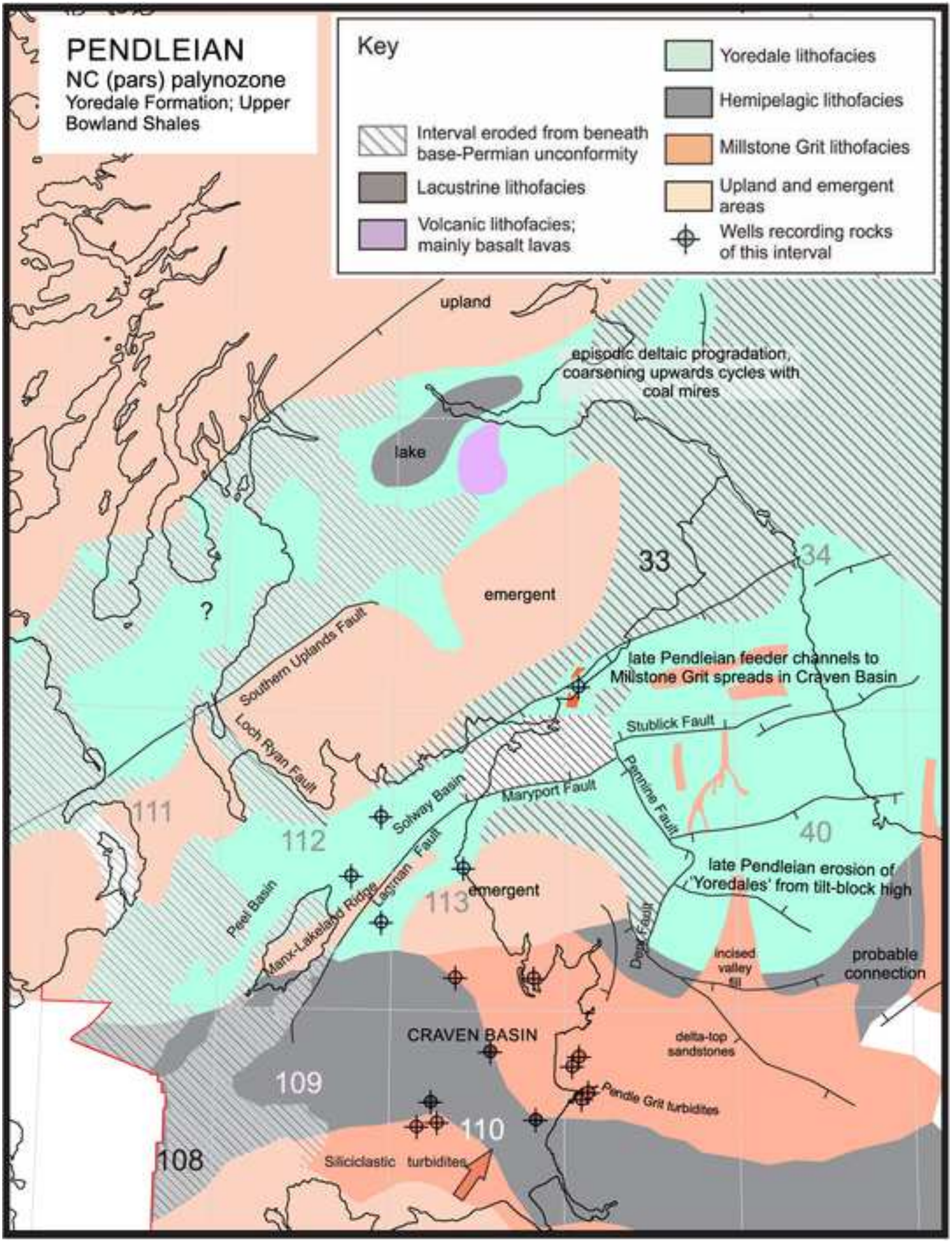

Figure 9

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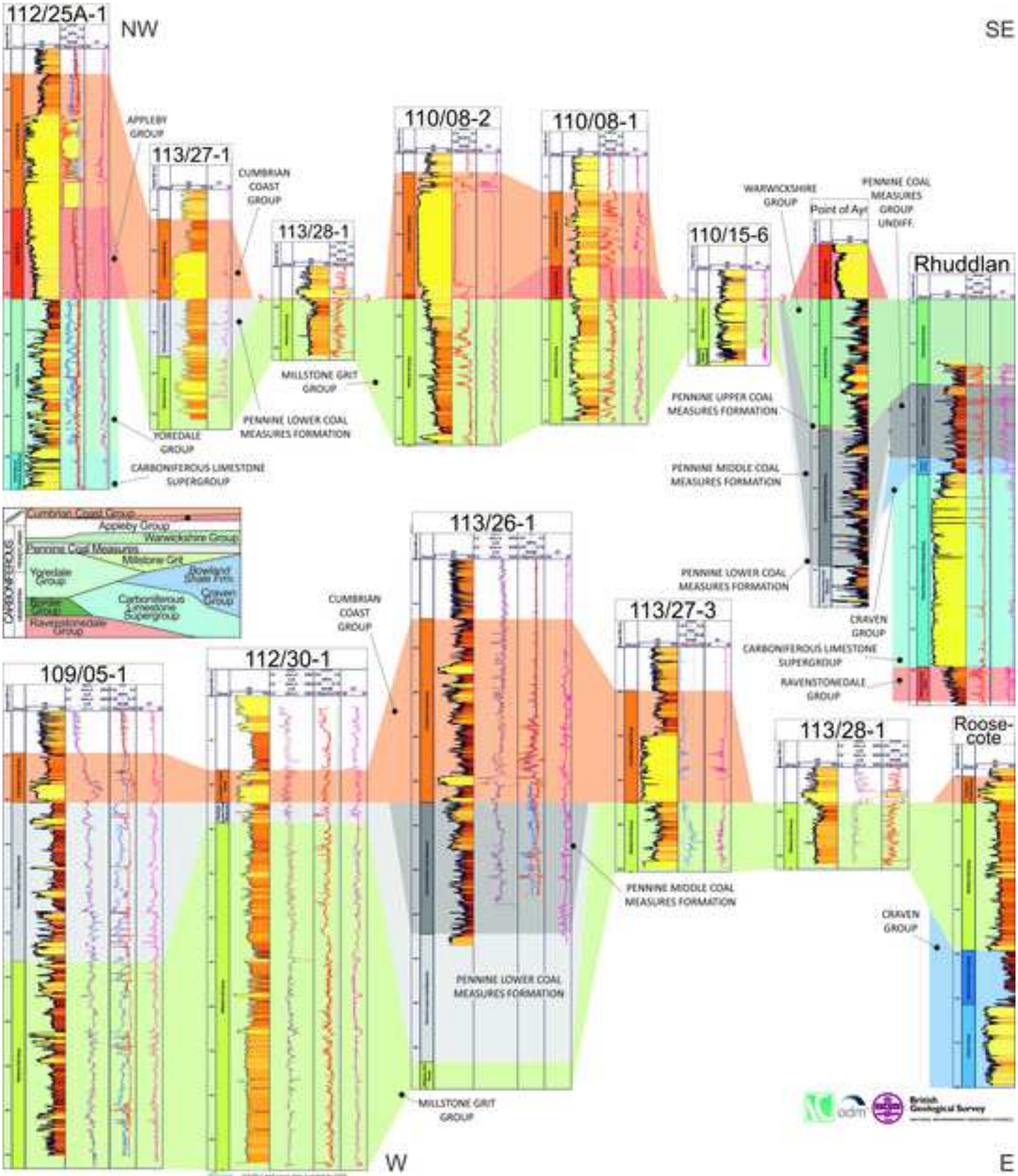

Figure 10

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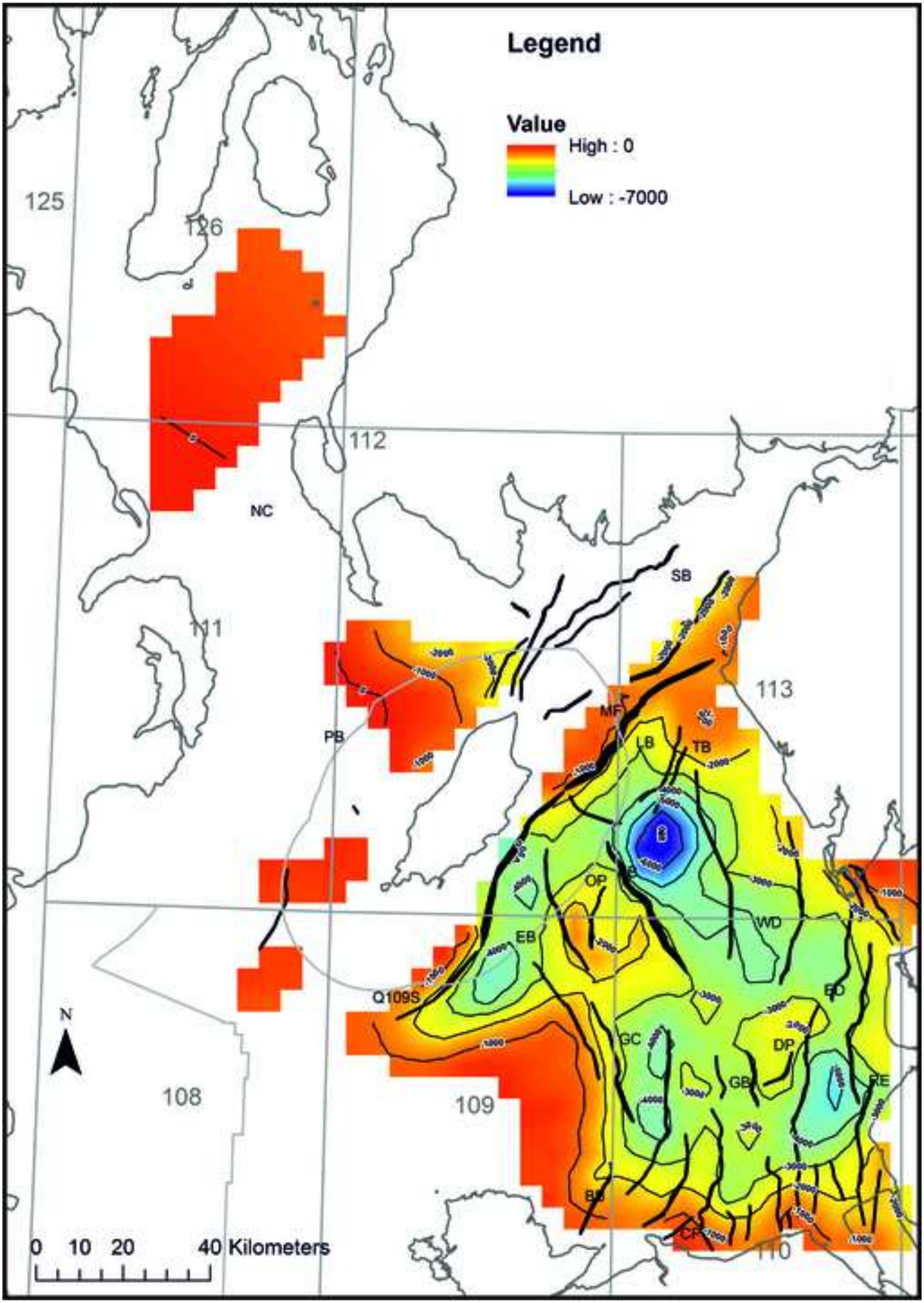

Figure 11

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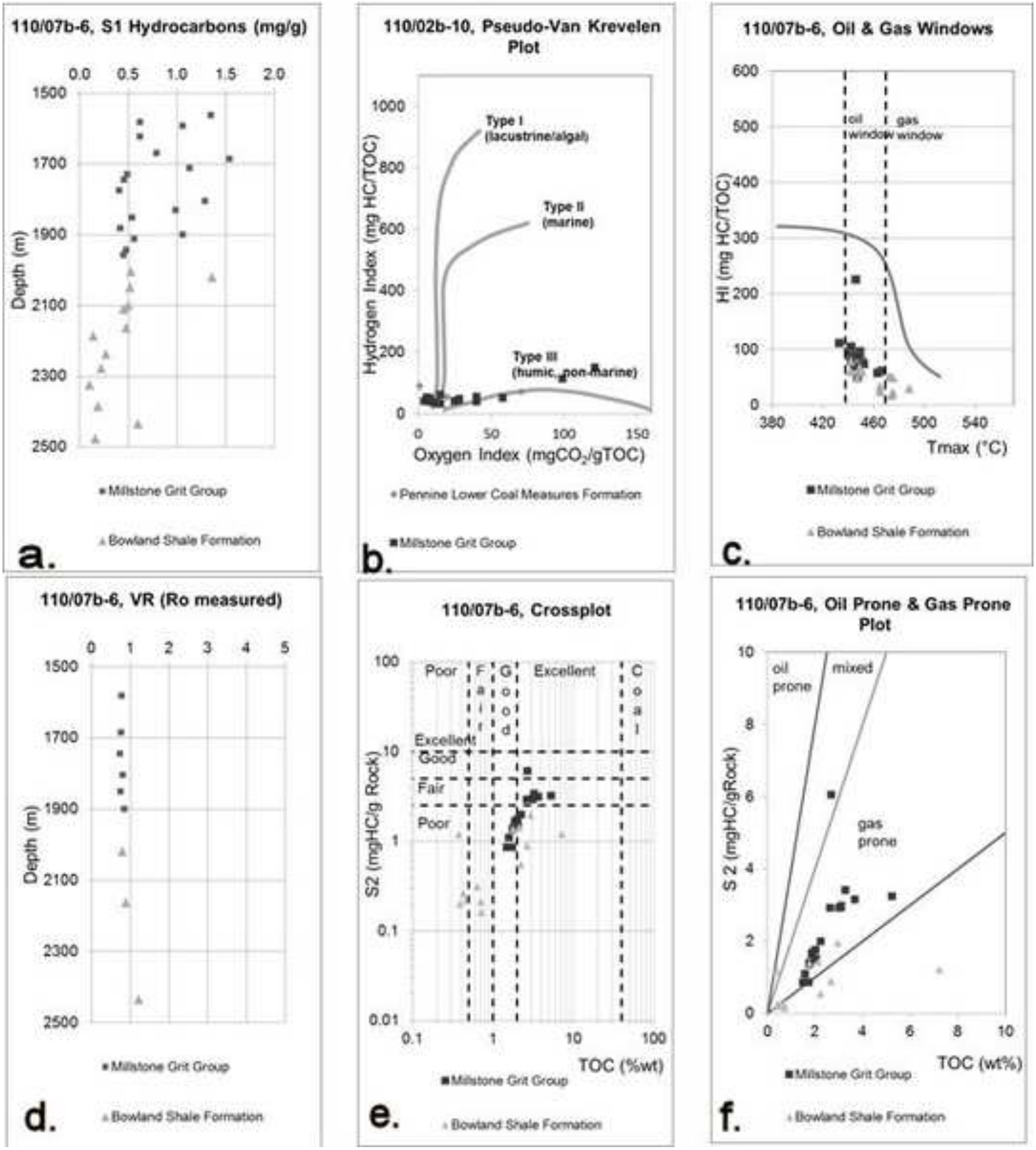

Figure 12

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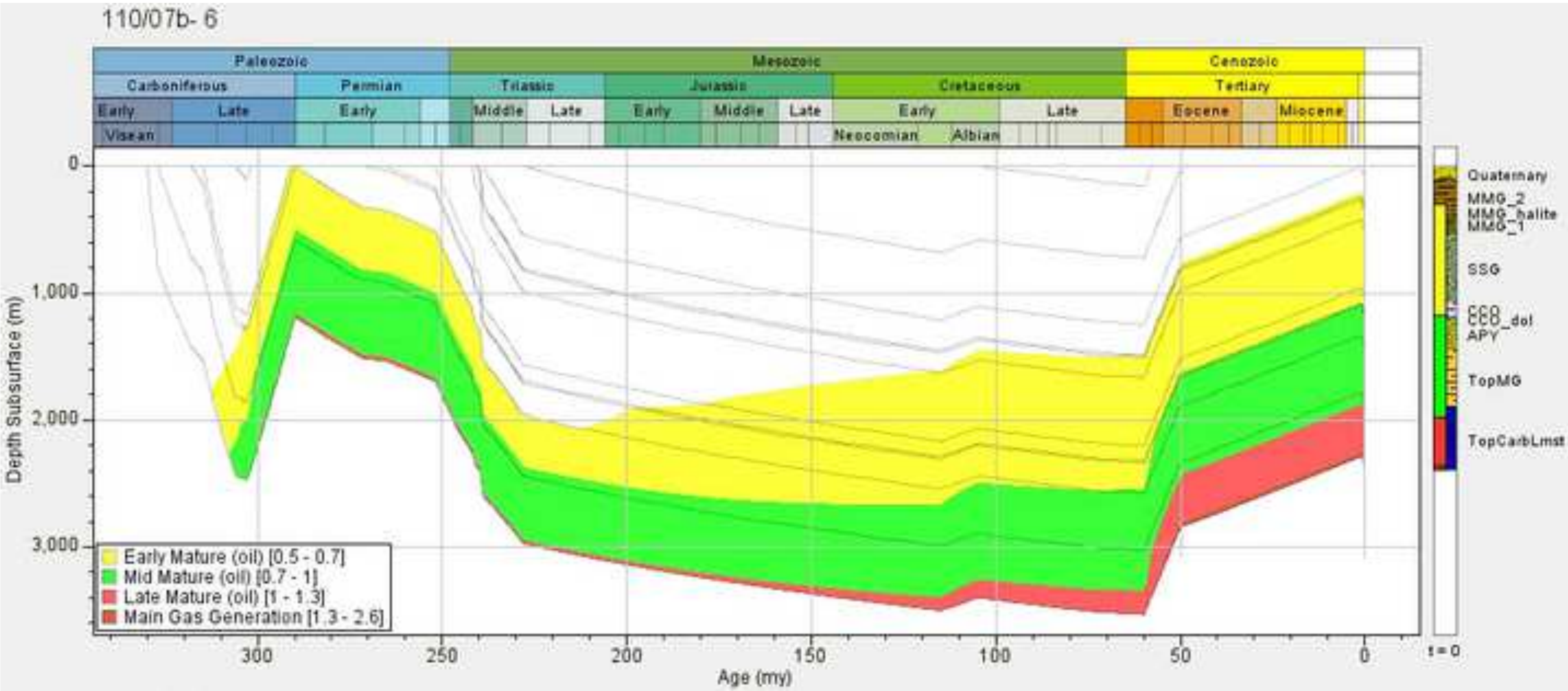

Figure 13 Click here to download Figure Fig13.jpg