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Carboniferous stratigraphical correlation and interpretation in the Irish Sea

Energy and Marine Geoscience Programme

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BRITISH GEOLOGICAL SURVEY

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Carboniferous stratigraphical correlation and interpretation in the Irish Sea

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Report; Stratigraphy, Carboniferous, East Irish Sea.

Front cover

View of the Great Orme, Llandudno, North Wales, comprising thick carbonate platform successions typical of the Carboniferous Limestone Supergroup of the Irish Sea and adjacent areas (P007274).

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Foreword

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

Acknowledgements

A large number of individuals involved with the 21CXRM have contributed to the project. We would particularly like to thank Mark Fellgett for well data gathering and preparation. We acknowledge LR Senergy for use of ODM ™ under license.

Gemma Campbell and colleagues (Centrica) are thanked for technical review of this report.

Contents

FIGURES

Summary

This report systematically details the stratigraphy and palaeogeography of Carboniferous rocks of the UK Irish Sea for the 21CXRM Palaeozoic project. Each stratigraphical group of Carboniferous or Permian age is described in turn. This report describes the stratigraphical correlation of Carboniferous strata of the report area using principally well data, but incorporates information from new seismic interpretations (Pharaoh et al., 2016a) to identify key unconformities.

The report provides:

- a systematic description of a spatially and temporally variable Carboniferous succession;
- Permian strata are also described for the succession above the Variscan Unconformity;
- a full incorporation of onshore knowledge is provided given the often limited offshore well data;
- a series of four correlation panels of key offshore and onshore wells/boreholes;
- a series of eight palaeogeogeographical maps which highlight the potential regional distribution of source and reservoir rock facies through selected time intervals during the Carboniferous.

A spreadsheet of well tops accompanies this report.

1 Introduction

The aim of the 21CXRM Palaeozoic Project is to stimulate exploration of the Devonian and Carboniferous plays of the Central North Sea – Mid North Sea High, Moray Firth – East Orkney Basin and in the Irish Sea area. The objectives of the project include regional analysis of the plays and building consistent digital datasets, and working collaboratively with the OGA, Oil and Gas UK and industry.

This report describes the stratigraphy and palaeogeography of the Carboniferous strata in Irish Sea, and integrates this with the adjacent onshore areas of the Midland Valley of Scotland, Northern Ireland, Northern England, North Wales and the Isle of Man. Four correlation panels (Section 3) were constructed across the region, tying in selected key wells in order to erect a framework for the Carboniferous strata and to provide regional-scale seismic ties (Figure 1; see Pharaoh et al., 2016a). The geological evolution of the offshore region has been interpreted in a number of key papers. The geology and hydrocarbon prospectivity of the Irish Sea was described by Newman (1999) and Floodpage et al. (2001). The Namurian source rocks in the East Irish Sea were described by Armstrong et al. (1997), implications of structure and stratigraphy on hydrocarbon prospectivity for the area by Williams and Eaton (1993), with specific fields within this area described by Haig et al. (1997), Yaliz (1997), Yaliz and McKim (2003) and Yaliz and Taylor (2003). Offshore, the lithostratigraphy of the Carboniferous rocks is described by Jackson and Johnson (1996), Jackson et al. (1987, 1995, 1997), and Chadwick et al. (2001) in the vicinity of the Isle of Man. The Carboniferous stratigraphy in all of these areas has been summarised by component chapters in Waters et al. (2011); specifically for the Irish Sea by Jackson et al. (2011).

The onshore geology of the Carboniferous of the Midland Valley of Scotland, Northern England, Northern Ireland, North Wales and the Isle of Man have been studied extensively, with succinct modern summaries of the lithostratigraphy, palaeogeography and tectonic evolution provided by Read (1988), Francis (1991), Chadwick et al. (1995), Akhurst et al. (1997), Browne et al. (1999), Chadwick et al. (2001), Mitchell (2004), Waters and Davies (2006) and Stone et al. (2010). The onshore Carboniferous lithostratigraphies have been revised recently on the basis of the distribution of the predominant lithofacies association throughout the sequence thus unifying, as far as is practicable, the many regional schemes that existed previously (Waters et al., 2007, 2009, 2011a; Dean et al., 2011 and references therein).

The stratigraphical scheme used in this report is summarised in Table 1 and Figure 2 and broadly follows Jackson et al. (2011) for the Carboniferous, but recommends abandonment of the threefold chronostratigraphic nomenclature of Garwood, Bisat and Kidston groups, which do not inform of the marked lithofacies variations contained within these groups. In this report, the onshore nomenclature is extrapolated offshore, wherever possible, as this provides the greatest understanding of these lithofacies variations.

1.1 DATA AND WORKFLOW

23 offshore wells have penetrated Carboniferous rocks in the UK Irish Sea. Their distribution is highly uneven (Figure 1), and many of the wells proved only a short succession of these strata. In the North Channel to Firth of Clyde no wells reached these strata, only two wells recorded significant thickness of rocks of this age in each of the Manx-Peel Basin, Solway Basin and Quadrant 109 areas. A much greater density of wells is present to the east of the region (East Irish Sea), particularly in the southern parts of Quadrants 113 and northern and central parts of Quadrant 110, containing the Morecambe Bay, Douglas, Hamilton gas fields and Lennox oil and field. Four correlation panels were constructed using 16 wells selected for the thick Carboniferous successions that they proved or as key ties to the seismic data (Pharaoh et al., 2016a).

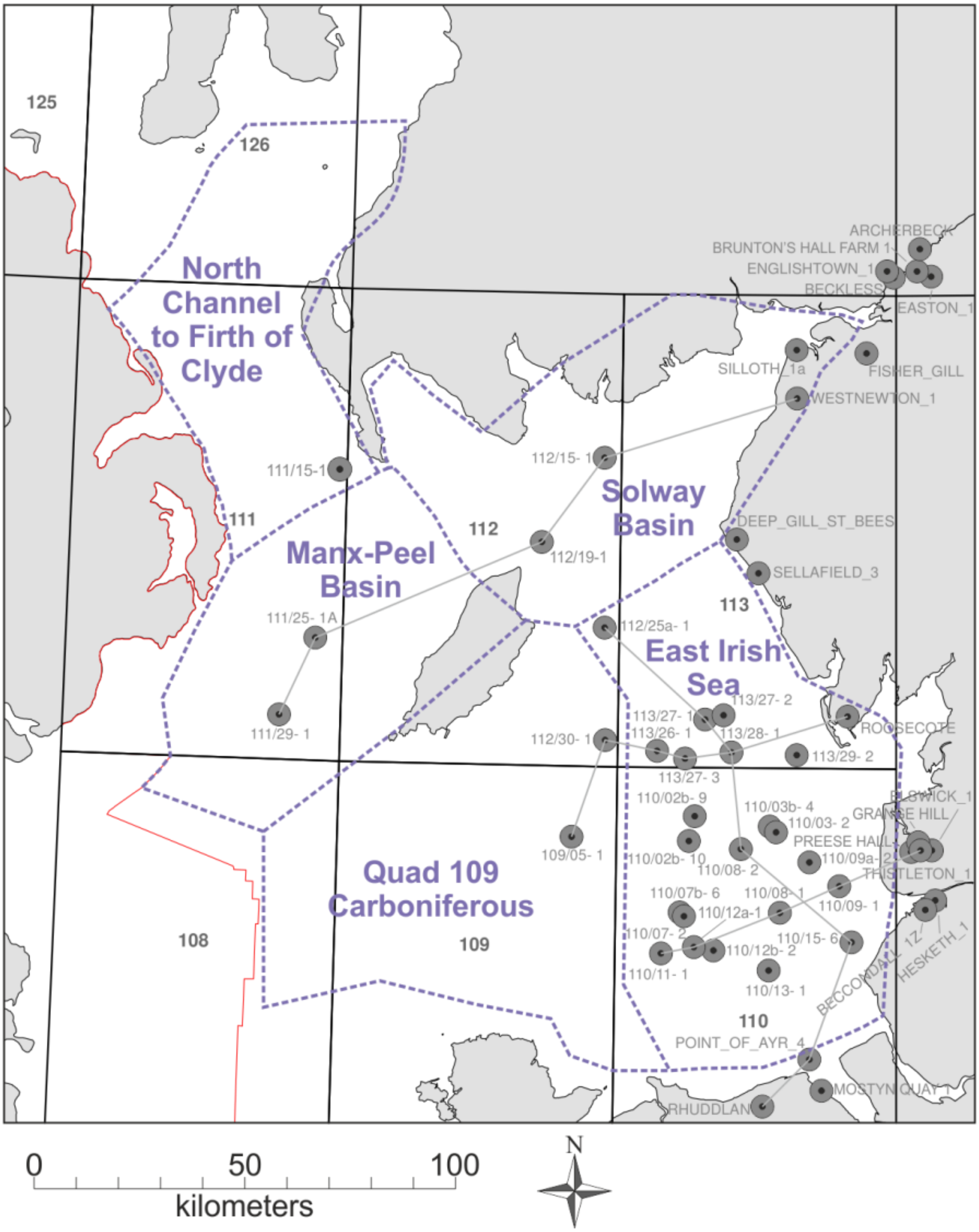

Figure 1 Distribution of the regions described in this report in relation to the offshore Quadrants and distribution of key offshore wells and onshore boreholes that prove Carboniferous strata (with the exception of 111/15-1).

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

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

A set of key onshore boreholes were selected to provide a link between the offshore and onshore stratigraphy. In the Solway Basin the wells selected are: Archerbeck (NY47NW/14), Becklees (NY37SE/3), Becklees 2 (NY37SE/19), Bruntons Hill Farm (NY47SW/44), Easton 1 (NY47SW/15), Englishtown 1 (NY37SW/6), Fisher Gill (NY25SE/16), Silloth 1a (NY15SW/1) and Westnewton 1 (NY14SW/32). The remaining boreholes/wells occur marginal to the East Irish Sea area, namely: Becconsall 1Z (SD42SW/11), Deep Gill St Bees (NX91SE/208), Elswick 1 (SD43NW/15), Grange Hill 1Z (SD33NE/37), Hesketh 1 (SD42NW/6), Mostyn Quay 1 (SJ18SE/22), Preese Hall (SD33NE/38), Rhuddlan (SJ07NW/28), Roosecote (SD26NW/19), Sellafield 3 (NY00SW/35) and Thistleton 1 (SD33NE/17). In addition, two wells, Liverpool Bay (SJ29NW/1) and Point of Ayr (SJ18NW/20) are actually located offshore, despite being classified as onshore boreholes.

For each well, composite logs, wireline geophysical logs (mainly gamma, caliper, sonic, neutron porosity and density) biostratigraphical and petrographical reports, and core photographs were examined. Full suites of wireline logs and biostratigraphy were unavailable for some wells. Previous interpretations of formation bases in completion reports and in published papers were reassessed, and modified where justified. Seismic data were also used to aid well interpretation. The biostratigraphical reports vary in date of completion, amount and quality of the data and the interpretation that they contain, resulting in uncertainty in the precise biostratigraphical age of parts of the sequence. For the Carboniferous sequences, the biostratigraphic zonation scheme contained in Waters et al. (2011) was used (see Appendix 1). Wells that penetrated short lengths of Carboniferous strata and those that lacked available digital wireline data were not re-interpreted.

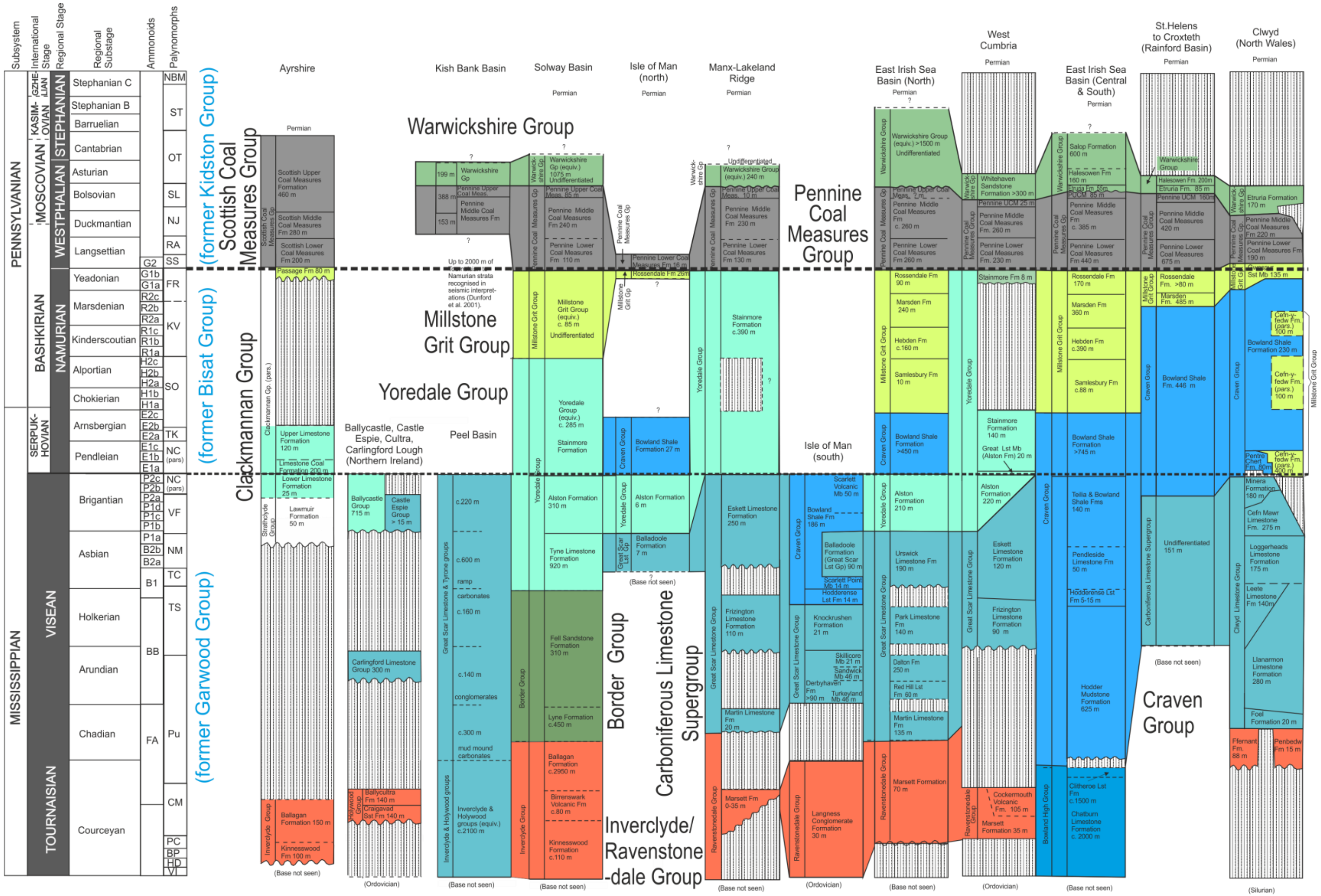

Figure 2 Carboniferous stratigraphical successions and correlation of the onshore UK and adjacent quadrants in the Irish Sea. The nomenclature, distribution and maximum thicknesses are those published in component chapters of the Geological Society Special Report on the Carboniferous (Davies et al., 2011; Jackson et al., 2011; Mitchell and Somerville 2011; Waters et al., 2011a, b, c, d)

1.2 ACCOMPANYING DATA SETS

Along with the descriptions of the units in Section 2, the key wells are shown in a set of correlation panels (Section 4); these are also available as A0 PDFs. The lithostratigraphic picks described in this report are also available as an Excel™ spreadsheet.

2 Carboniferous

This section provides a systematic description of the Carboniferous strata proved in offshore wells, namely the Ravenstonedale Group, Carboniferous Limestone Supergroup, Border Group, Yoredale Group, Craven Group (with specific details on the component Bowland Shale Formation), Millstone Grit Group, Pennine Coal Measures Group (and component formations) and Warwickshire Group.

The Inverclyde Group, as defined by Paterson and Hall (1986) in the Midland Valley of Scotland, is also present south of the Southern Uplands in the Thornhill Basin (Dumfries and Galloway coastline) and adjacent offshore Solway Firth area and in the northern and central parts of Northumberland Basin. The group, of Courceyan – Chadian (Tournaisian to early Visean) age (Figure 2), will be present in the Solway Basin area, but has not been proved in any offshore well or onshore borehole adjacent to the Irish Sea and is hence not described in detail. The group is also present in the Firth of Clyde, present at outcrop on the Mull of Kintyre and Arran, with the offshore extent interpreted on seismic in the Firth of Clyde extending across to the coast of Northern Ireland (Pharaoh et al., 2016a).

The Inverclyde Group was deposited in a continental to peritidal environment and as such, comprises a broad range of lithologies that include: interbedded fine- to coarse-grained sandstones, mudstones, limestones, dolostones and locally anhydrite (present in the subsurface only). Some rootlet and thin coal seams can also be present, though are generally rare. Some limestones show evidence of pedogenesis. Mudstone horizons can also contain thin beds of limestones and dolomite. The lower part of the group within the Solway−Northumberland Basin is defined by the Kinnesswood Formation, which represents the deposition of a series of alluvial fans in a calcrete-rich setting. The upper part of the group in the same basin is defined by the Ballagan Formation, similarly representing the deposition of alluvial fans, but also including fluviodeltaic sediments intercalated with lacustrine and arid coastal plain.

The Strathclyde Group, of Visean age, is limited in extent to the Midland Valley of Scotland and is not described in detail here, but is defined fully by Paterson and Hall (1986) and Dean et al. (2011). The group comprises mainly ‘Heterolithic clastic and non-marine carbonate’ facies strata deposited in fluviatile, deltaic and lacustrine or lagoonal environments. The sedimentary rocks consist of interbedded sandstone, siltstone and mudstone (including oil-shales) with common seatearth, coal and sideritic ironstone. The igneous rocks, which dominate parts of the western Midland Valley of Scotland and are interpreted on seismic in the Firth of Clyde (Pharaoh et al., 2016a), comprise typically mildly alkaline lava, tuff and volcaniclastic beds (Clyde Plateau Volcanic Formation).

The Clackmannan and Scottish Coal Measures groups of the Midland Valley of Scotland (Figure 2), can be broadly equated lithologically with the Yoredale and Millstone Grit groups and Pennine Coal Measures Group, respectively.

2.1 RAVENSTONEDALE GROUP

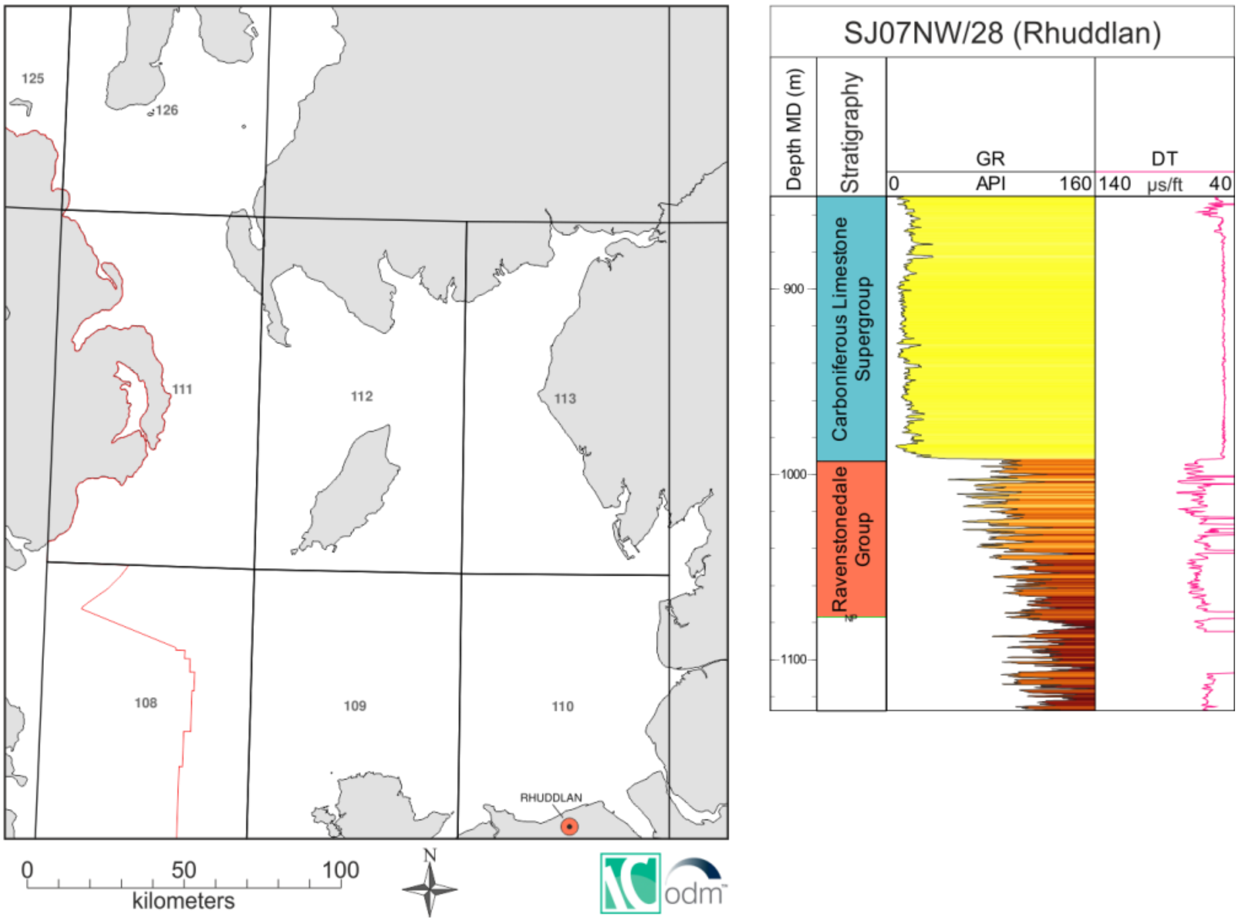

Figure 3 Distribution of the wells where the Ravenstonedale Group has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Ravenstonedale Group defined by Dean et al. (2011), named after the Ravenstonedale area of Cumbria, comprises continental and peritidal facies of Tournaisian to early Visean age. Adjacent to the Irish Sea, key formations include the Marsett Formation, present in west and south Cumbria and Langness Conglomerate Formation of the Isle of Man. Isolated formations in North Wales (Lligwy Sandstone, Menai Straits, Ffernant, Penbedw, Fron-Fawr and Pant formations), though not part of the Ravenstonedale Group comprise strata of the same facies and are included here (Waters et al., 2011).

Previous Names

Part of the former offshore Garwood Group of Jackson and Johnson (1996). Onshore the unit has variously been known as the Ravenstonedale Limestone, Basement Beds and Basement Conglomerate.

Geological extent

It comprises a typically thin succession, with geographically isolated outcrops present across Cumbria, North Yorkshire, north Lancashire and Isle of Man and inferred to be present offshore in areas between. For this study a number of isolated alluvial facies deposits present in North Wales are included within this group, though in fact they are stand-alone formations (Waters et al. 2011). The group is not proved in wells offshore but is interpreted on seismic in the Quad 109 and East Irish Sea areas (Pharaoh et al., 2016a). However, such a laterally extensive succession is unrepresentative of the alluvial facies seen onshore, which developed marginal to upland areas, and it is probable that the lithologies of the succession interpreted from the seismic data may be different to the typical Ravenstonedale Group.

Lithology

The Ravenstonedale Group typically includes green to green-grey and/or variably reddened pebble conglomerate (locally calcite cemented), lithic sandstone, sandstone and mudstone (Dean et al., 2011). Evaporitic deposits have been recorded in boreholes and pedogenic carbonates occur within the sandstones. Conglomerates have a local provenance, and basaltic lava flows (Cockermouth Volcanic Formation) occur locally within the alluvial fan facies. The most diverse lithological development is in the western part of the Stainmore Basin and northern part of the Askrigg Block, where limestone and dolostone make up a significant component of the group. The Langness Conglomerate Formation of the Isle of Man comprises reddish brown, generally poorly sorted, typically clast-supported conglomerate with subordinate interbedded sandstone (Dickson et al., 1987; Chadwick et al., 2001). In North Wales the formations include reddened alluvial breccias, conglomerates, sandstones, siltstones and mudstones, with replacive calcareous nodules (‘cornstones’), and thin beds of variegated, red and green, argillaceous, nodular limestone or dolomite are present throughout. All component formations are marked by clast compositions directly sourced from Lower Palaeozoic strata present in neighbouring palaeo-highs.

Key wells

Rhuddlan (1076−995 m). A marked high gamma response occurs at the boundary of the relatively ‘clean’ Carboniferous Limestone Supergroup and the relatively more argillaceous, underlying Ravenstonedale Group (Figure 3).

Lower boundary

The Ravenstonedale Group is unconformably underlain by strata of Ordovician to Devonian age, including the Kendal Group in Cumbria, the Wensleydale Granite in North Yorkshire, Manx Group in the Isle of Man, and Silurian rocks in North Wales. The Ravenstondedale Group onlaps palaeohighs associated with the Caledonian Orogeny and subsequent phase of Late Devonian to Early Carboniferous north−south crustal extension and associated horst and graben development. The Caledonian Unconformity is markedly angular.

Upper boundary

Conformably overlain by carbonates of the Great Scar Limestone Group in northern England and Isle of Man and the Clwyd Limestone Group of North Wales; both carbonate successions belong to the Carboniferous Limestone Supergroup. This boundary is well illustrated by the ‘cleaner’ gamma response of the overlying Carboniferous Limestone Supergroup compared with the higher gamma response of the Ravenstonedale Group.

Age

Courceyan – Asbian (Tournaisian –Visean)

2.2 CARBONIFEROUS LIMESTONE SUPERGROUP

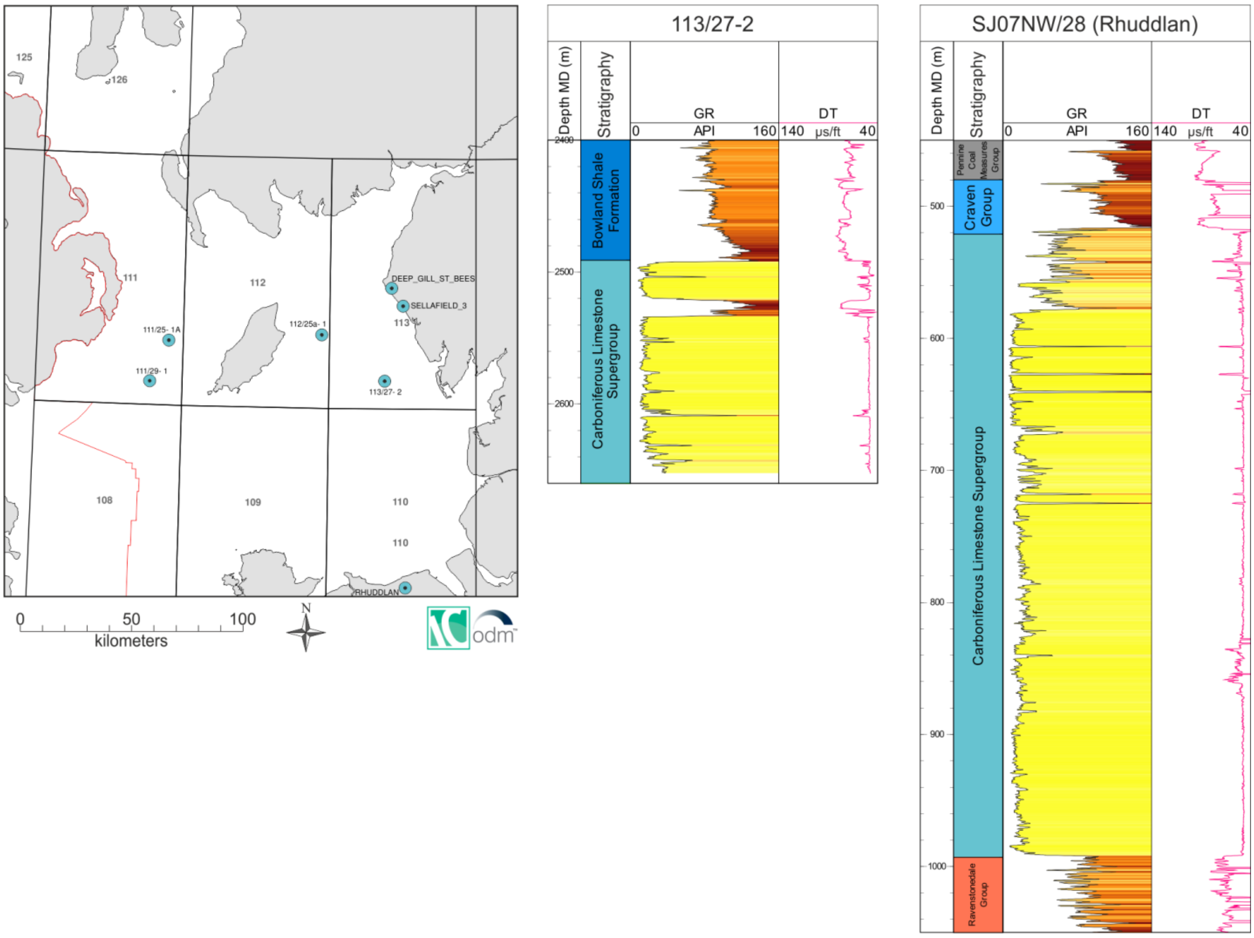

Figure 4 Distribution of the wells where the Carboniferous Limestone Supergroup has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term was proposed by Waters et al. (2007) to encompass a number of disparate Early Carboniferous carbonate successions, which in the study area include the Great Scar Limestone, Bowland High, Holme High Limestone, Trawden Limestone, and Clwyd Limestone groups. The term is here proposed to also include the Carlingford Limestone Group of Northern Ireland.

Previous Names

Carboniferous Limestone Series

Geological extent

The Carboniferous Limestone Supergroup forms two broad belts. Within the onshore periphery of the Irish Sea, the northern belt is present in west and south Cumbria (up to 740 m thick), North Yorkshire (up to 800 m thick), the southern part of the Isle of Man (up to about 157 m thick) and in Carlingford Lough, Northern Ireland (300 m thick) and is proved within intervening areas offshore in the northern part of the East Irish Sea and Manx-Peel Basin. The maximum geographical extent, during the Asbian, may also have extended into the southern part of the Solway Basin and North Channel areas. The southern belt is present onshore in North Wales, well exposed in the Great Orme, Llandudno (see front cover) and extends offshore into the southern parts of Quad 109 and East Irish Sea areas. The two belts are separated by basinal successions of the Craven Group. Onshore, in northern England carbonates of the supergroup developed on local structural highs, e.g. the Bowland, Central Lancashire and Heywood highs.

Lithology

The characteristic lithologies of the supergroup are predominant limestones and dolostones; the limestones vary from bioclastic with common shelly fauna and crinoids, to micritic. Algal beds and coral biostromes are also present. The supergroup shows a trend from dark grey Courceyan to Chadian limestones and dolostones, commonly stromatolites and oncolites, dark grey Arundian to Holkerian argillaceous limestones, often with Waulsortian bioherms, to pale grey late Asbian to early Brigantian limestones, typically dominated by an upward thinning of limestones beds with prominent development of palaeokarstic surfaces (Waltham, 1971; Waters et al., 2016). Sandstone can be locally common, especially in the upper part of the supergroup. Apron knoll reefs are developed along the southern margin of the Askrigg Block and southern part of the Isle of Man, but are not recorded between in Furness (south Cumbria). Sellafield 3 borehole provides an important reference for the supergroup succession. The upper part of the Carboniferous Limestone Supergroup from 1473.82-1515.75 m, shows grainstones, dolomitized below the Variscan Unconformity, with increased frequency of mudstone partings and palaeokarstic surfaces, pseudobreccias above about 1515 m which Barclay et al. (1994) recognises as late Asbian carbonates. Much of the underlying limestones, 1515.75-1615.45 m, are mainly bioclastic packstones with subordinate dolostones are of Holkerian age, the base of which succession is taken at the base of a rare mudstone. The basal sandy packstone limestones from1615.45-1622.82 m., is equated by Barclay et al. (1994) with the Martin Limestone Formation is of Chadian age.

Key wells

Within the Manx-Peel Basin the supergroup is present in 111/29-1 (1435–1096 m), of Asbian age (TC to NM Biozone) and inferred to be present in 111/25-1A (1668–1596 m). In the northern part of the East Irish Sea the supergroup is proved in 112/25a-1 (2780–2690 m) and 113/27-2 (2660–2491 m) of Brigantian age. Onshore, the succession is proved in Deep Gill St Bees (568–531 m), Sellafield 3 (1623–1474 m) and Rhuddlan boreholes (995–521 m). Well 113/27-2 displays linear, 'box-car' profiles of low gamma and very high velocity in the limestone intervals, separated by partings and thicker interbedded units of high gamma, lower velocity mudstone and siltstone; contacts with the interbedded lithologies are abrupt (Jackson and Johnson, 1996). Well 112/25a-l shows a more erratic profile with low gamma limestone and sandstone signatures interrupted by high gamma mudstone and siltstone spikes (Jackson and Johnson, 1996). This profile superficially looks like a continuation of the overlying Yoredale Group. However, the limestones are thicker, representing the dominant lithology and are described as light to medium grey. The presence of common mudstone and sandstone partings is seen to be equivalent to the succession of the Great Scar Limestone Group present in west Cumbria (Akhurst et al., 1997). In west Cumbria the Carboniferous Limestone Supergroup ranges up into the early Pendleian. This is consistent with the miospore zonation which suggests the top of the supergroup occurs within a succession ranging from Visean to early Namurian in age. In Well 111/29-1 the succession proved between 1096 m and 1113 m, at least in part Asbian in age, comprises brown to dark brown to beige microcrystalline to crystalline chalky limestones with chert traces and beds of brown and dark brown silty and slightly calcareous claystone, locally dark red-brown. This succession is more typical of the Yoredale Group, though the Asbian age would suggest if this is the case it would represent an early development of the group, equivalent to the Tyne Limestone Formation present onshore. Unfortunately, erosion at the base of the Variscan Unconformity has removed the Brigantian succession and prevents unequivocal recognition of Yoredale Group- type siliciclastic-carbonate cycles.

The upper part of the supergroup in the Rhuddlan Borehole, from c. 580 to 520 m, has a more serrated and markedly higher gamma response. This may represent the late Brigantian Minera Formation of the onshore Clwyd Limestone Group, in which calcareous sandstones and thin mudstones are a common component in addition to thick limestones (Waters et al., 2009).

Lower boundary

The Carboniferous Limestone Supergroup typically rests with an angular unconformity above lower Palaeozoic or older strata. Where the supergroup has a disconformable base, the boundary is taken as the lowermost limestone or dolostone above successions of sandstone, conglomerate or anhydrite. The base is not proved in any offshore well, but is proved in the Rhuddlan borehole, where the supergroup rests upon alluvial facies. In the Rhuddlan borehole (SJ07NW/28) the lower boundary is defined by a marked increase in the gamma response of the Ravenstonedale Group.

Upper boundary

Within the Manx-Peel Basin and parts of onshore west Cumbria, the upper boundary is marked by the Variscan Unconformity, overlain by Permian strata. Elsewhere, it is typically a sharp boundary whereby the limestones of the supergroup are overlain by the dark mudstones of the Craven Group (including Bowland Shale Formation) in the south of the region, or the mudstones, sandstones and thin limestones of the Yoredale Group in the north.

Age

Courceyan – Pendleian (Tournaisian – Early Namurian)

The supergroup is Chadian to Asbian in age in North Yorkshire, Tournaisian to Pendleian in Cumbria, Arundian to Asbian in age in the south Isle of Man and Arundian in Northern Ireland.

2.3 BORDER GROUP

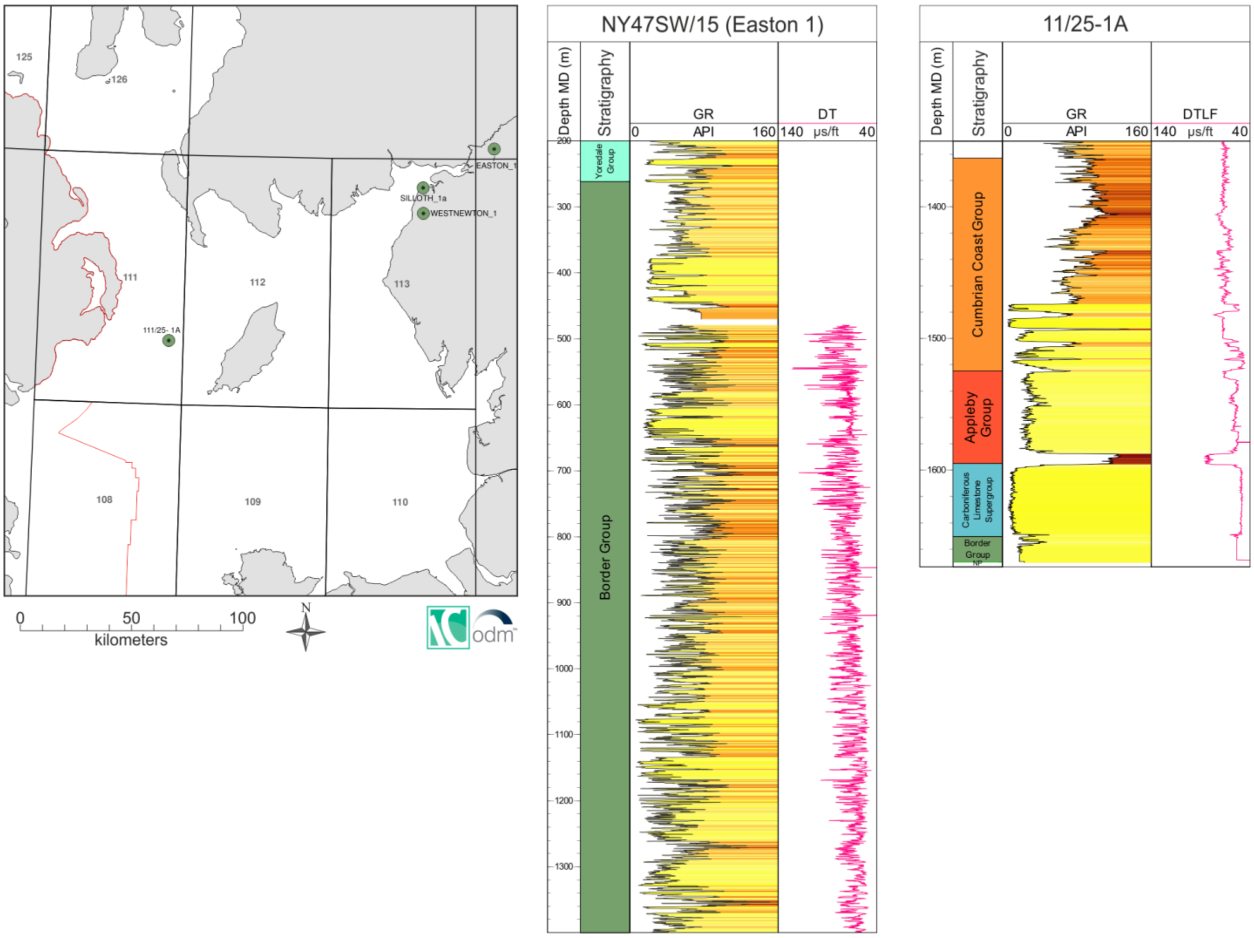

Figure 5 Distribution of the wells where the Border Group has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Border Group is here used as proposed by Waters et al. (2007) and defined by Dean et al. (2011).

Previous Names

Previous names include the Lower and Middle Border Group of Day (1970) in the Bewcastle area (Northumberland Basin). Offshore, the Border Group was previously part of the Garwood Group.

Geological extent

The Border Group is proven in the Solway−Northumberland Basin, including onshore in the periphery of the Irish Sea in the Solway Firth, Annandale and Langholm. The thickest development is at Bewcastle where base of the unit is not seen (Day, 1970). Here it comprises the Lyne Formation (formerly Lower Border Group) and the Fell Sandstone Formation (formerly Middle Border Group). The group is not proved in offshore wells but it is picked on seismic in the Solway Firth area (Pharaoh et al., 2016a), showing the top of the Fell Sandstone Formation equivalent extending across the Solway Basin, extending westward to a line between the Mull of Galloway and the Isle of Man.

Lithology

The Border Group comprises interbedded sandstones, siltstones and limestones, with conglomerate and ferroan dolostone ("cementstone"). It typically occurs in the Northumberland Basin as a lower Lyne Formation and upper Fell Sandstone Formation. The Lyne Formation typically comprises cyclical sequences of fine-grained subarkosic sandstone, siltstone, mudstone, and thin limestone in which thin oolitic pellet beds are characteristic (Dean et al., 2011). A distinctive facies has been proved in the Easton 1 borehole in which the Lyne Formation is represented by the Easton Anhydrite Member, of grey or white anhydrite interbedded with limestone, shale, siltstone and sandstone 1153 m thick (base not seen). The Lyne Formation passes upwards into the Fell Sandstone Formation, which in the central part of the Solway−Northumberland Basin represents a continuation of the cyclical successions of fine-grained subarkosic sandstone, siltstone, mudstone and thin limestone present in the underlying Lyne Formation, although in the Fell Sandstone the sandstones are thicker and the limestones thinner (Day, 1970). Seatearths are common in the upper part of the formation.

Key wells

Key wells include Easton 1 (2260−262 m) described by Ward (1997), Westnewton 1 (2044−1588 m) and Silloth 1a (1342−1312 m) and offshore in Well 111/25-1A (Figure 5). The upper boundary of the Border Group has variable gamma response. Where it is conformably overlain (by the Yoredale Group) the boundary is marked by a subtle low gamma response (Silloth 1a). In instances where the group is overlain unconformably, the relative gamma response is usually better defined (Easton 1).

Well 111/25-1A comprises interbedded very fine- to fine-grained clean sandstone, siltstone, red claystone and thin limestone below 1657.5m. It is overlain (from 1649.20 m to 1657.5 m) by a varicoloured brown to reddish beige limestone with a slightly higher gamma and lower resistivity response compared to the overlying carbonates of the Carboniferous Limestone Supergroup. The upper boundary of the Border Group, taken at 1649.20 m, corresponds with a prominent gamma peak, low density deflection, marked fall in resistivity (LLD log) and decrease in sonic log. The lower heterogeneous part of the succession attributed to the Border Group is most reminiscent of the Lyne Formation. The carbonate may represent may represent a quasi-marine stramotolitic limestone typical of the Lyne Formation, but insufficient information is available on the nature of the limestone in this well to confirm this.

The Border Group succession described by Ward (1997) in Easton 1 shows the following lithological variations. From 2260 to 1819 m, broadly of Chadian to Arundian age, is a cyclic succession with cycles 12-15 m thick. Cycle bases are marked by limestones, mainly dolomitic, algal and oolitic, which are relatively thin and are predominantly interbedded with anhydrite forming composite limestone-anhydrite beds about 2-6 m thick that contain only minor amounts of shale. The proportion of shales or claystones in the succession increases downhole making up to 50-70% of the total cycle thickness; sandstones are numerous but thin. From 1819 to 1180 m these beds consist of nine large cyclic sequences of limestones, shales, sandstones and anhydrite, cycles ranging from 25 to 82 m thick. Limestones make up more than 50% of the thickness and are from 15-24 m thick. Anhydrite beds are present up to a depth of 1054 m. The transition into Holkerian strata is uncertain, but thick sandstones thought to be of this age are present to a depth of 650 m and numerous coals to a depth of 700 m and below 716 m limestones become thicker.

In Westnewton 1 Borehole, the Arundian part of the Border Group succession from to 2044 to 1847 m, comprises an upper 53 m dominated by light to dark grey limestones, with dark grey mudstone and white sandstones becoming more significant in number and thickness below, with carbonates thinner and more commonly dolomitic. The overlying Holkerian succession (1847-1588 m) continues to show the presence of common and thick limestones, up to about 50 m thick in the upper part of the succession. The siliciclastic Fell Sandstone Formation is not evident in this Holkerian succession.

Lower boundary

In Annandale, the Lyne Formation is conformable on interbedded siltstones, sandstones and ferroan dolostones ("cementstones") of the Kirkbean Member of the Ballagan Formation (Inverclyde Group), as seen in the Hoddon No.2 Borehole (NY17SE/3, NY1641 7285). At Kirkbean, the Lyne Formation is presumed to rest unconformably on the Ballagan Formation, and comprises siltstone and dolomitic limestone with fine-grained sandstone, contrasting with the predominantly thin dolomitic limestone and fine-grained sandstone Ballagan Formation sequence. At Brampton, the base of the unit is taken at the base of interbedded thick sandstones with thin limestones and mudstones of the Fell Sandstone Formation, which rests conformably on the Ballagan Formation.

Upper boundary

In Annandale, thick medium- to coarse-grained sandstones, siltstones and seatrocks of the Fell Sandstone Formation of the Border Group are overlain conformably by interbedded sandstone, siltstone and limestone the Tyne Limestone Formation (Yoredale Group). Locally in the Annandale and Langholm districts, the base of the Tyne Limestone Formation is represented by interbedded tuffaceous sandstones and siltstones of the Glencartholm Volcanic Beds. In Bewcastle the base of the Tyne Limestone Formation is represented by marine fossiliferous limestone and mudstone of the Clattering Band, with common colonial corals, including *Lithostrotion martini* and *L. portlocki* and gigantoproductids (*Semiplanus* sp.). The upper boundary of the Border Group is diachronous across the Solway−Northumberland Basin.

Age

Courceyan to Holkerian (Tournaisian – mid Visean)

2.4 YOREDALE GROUP

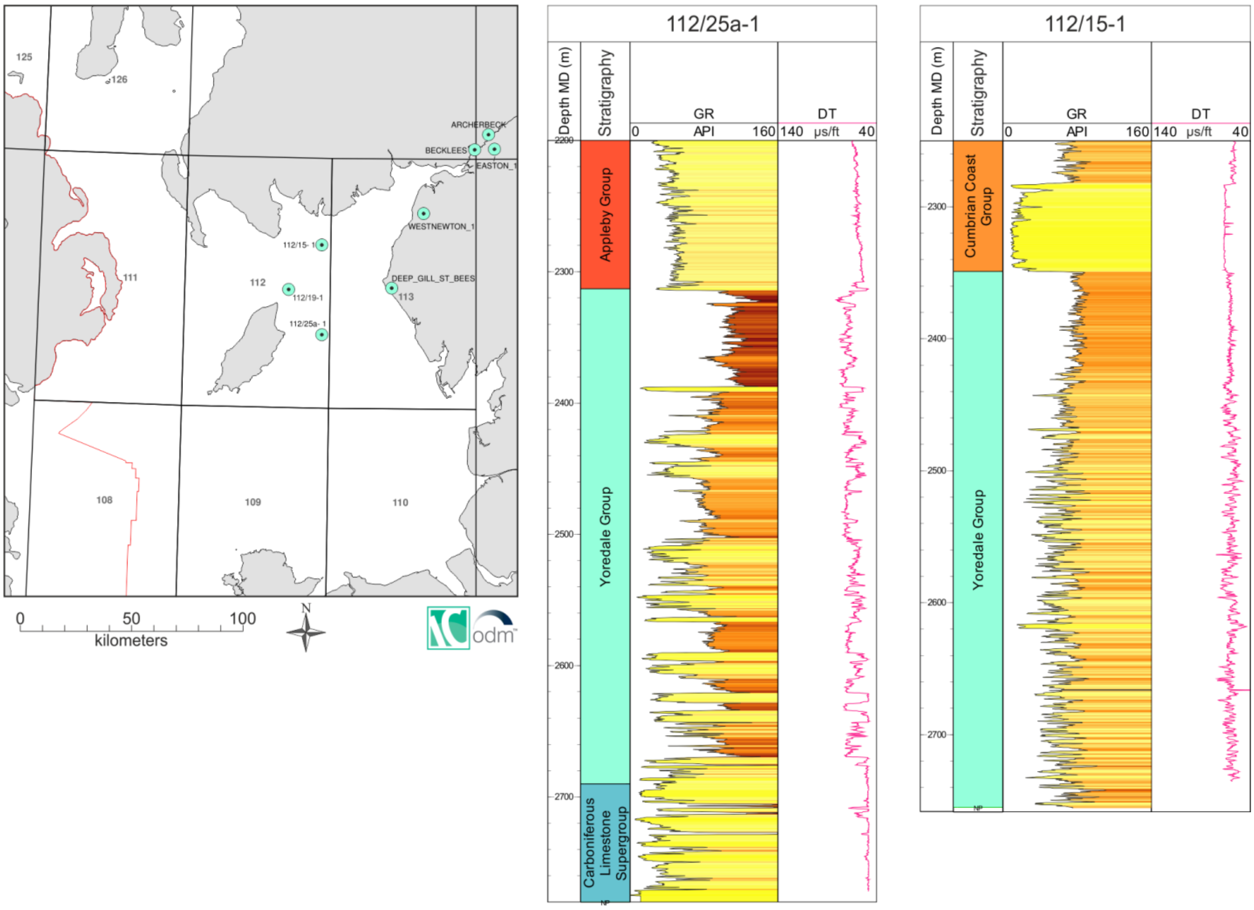

Figure 6 Distribution of the wells where the Yoredale Group has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Yoredale Group is here used as proposed by Waters et al. (2007) and defined by Dean et al. (2011).

Previous name

Previous names include the Liddesdale and Upper Border Group in the Solway−Northumberland Basin, Wensleydale Group on the Askrigg Block, Alston Group on the Alston Formation, Yoredale Beds. Offshore, the Yoredale Group was previously part of the Garwood and Bisat groups.

Geological extent

The Group is found across Northern England, north of the Craven Fault System in North Yorkshire, Solway−Northumberland Basin and the Thornhill Basin (Dumfries and Galloway). In the north of the Isle of Man undifferentiated strata assigned to either the Great Scar Limestone Group or the Yoredale Group occurs in the Ballavaarkish (Shellag North) Borehole [NX 4625 0070] between 172.34 and 179.60 m depth (Chadwick et al., 2001). An equivalent of the Yoredale Group is evident with the Lower Limestone and Upper Limestone formations (Clackmannan Group) in Ayrshire and is inferred to extend into the Firth of Clyde (Midland Valley of Scotland). In Strangford Lough, southeastern Northern Ireland, the Strangford Group of marine limestones and shales represents a local equivalent of the Yoredale Group (Mitchell, 2004). Offshore, the group extends across the Solway Basin, the northern parts of the Quad 109 and East Irish Sea areas, proved from wells and seismic data; the extent in the Manx-Peel Basin is constrained from seismic data only (Pharaoh et al., 2016a).

Lithology

The Yoredale Group is characterised by a cyclic succession comprising, in ascending order: laterally extensive limestone, marine mudstone, sandstone, seatearth and coal (the coal is not always preserved). Each complete cycle, which typically ranges from 5–90 m thick, represents a marine transgression and regression. The limestones and mudstones contain marine fauna including: crinoids, brachiopods, foraminifera, and sometimes rare examples of ammonoids (Stone et al., 2010). The limestones are typically mid to dark grey, thin-bedded and biomicritic. The sandstones are typically pale grey, fine- to medium-grained and quartzitic to sub-arkosic (Dean et al. 2011), but with large fluvial channels of coarser grained, locally pebbly, quartz-feldspathic locally present (Waters et al., 2014).

Key wells

Well 112/15-1 (2755−2349 m) mainly ?late Brigantian to Pendleian in age, 112/19-1 (2023−1882 m) of Visean to earliest Namurian age, 112/25a-1 (2690−2312 m Figure 6), Archerbeck, Becklees, Westnewton 1, Deep Gill St Bees and Easton 1. Typical gamma log responses of the intercalated succession, as developed in 112/25a-l (Figure 6) are spiky to erratic, consisting of low gamma, high velocity limestone, succeeded abruptly by a high gamma mudstone that coarsens upwards to a thin clean or multi-storey low gamma high velocity sandstone (Jackson and Johnson, 1996). Due to the variable lithologies present in the Yoredale Group, where the group is unconformably overlain, the potential erosion and subsequent loss of the upper parts of the group can lead to a variable initial gamma responses. This is best illustrated in (112/25a-1) where the clean gamma and higher sonic response of the overlying Appleby Group are underlain by the high gamma, relatively slower sonic responses, in this instance indicating a reddened mudstone horizon between 2312 to 2388 m. Similarly, in 112/15-1 the succession above c. 2430 m is more argillaceous and lacks the sandstones seen elsewhere in the group. This interval comprises reddened mudstone and siltstone, locally dark grey, but with the presence of a breccia and dolostone which led to the interpretation in the composite log as Permian strata. In Figure 6 the Permian low gamma responses of the Appleby and Cumbria Coast Groups contrast to the relatively higher response of the Yoredale Group.

In Easton 1 the base of the Yoredale Group at 262 m is taken at the base of tuffaceous clays interpreted to be equivalent to the Glencartholm Volcanic Beds, which typically mark the base of the Asbian succession. A further volcanic bed is present at about 106 m depth, with the succession between to two volcanic intervals associated with thin sandstone-dominated cycles. In Westnewton 1 Borehole, the Asbian part of the Yoredale Group interval from 1588 to 612 m shows typical Yoredale cyclicity with common thin coal seams, overlain by limestones typically up to 10 m thick, in turn overlain by a coarsening upwards mudstone to sandstone intervals. The overlying Brigantian part of the borehole, from 612 to 200 m shows cycles in which the limestones are a more significant component of each cycle.

Lower boundary

In the south of Scotland, the group is conformably underlain by the Border Group. The boundary defined by the change from the cyclic facies of the Yoredale Group into the thicker medium- to coarse-grained sandstones of the underlying Border Group.

In northern England, the Yoredale Group is underlain by the Great Scar Limestone Group (Carboniferous Limestone Supergroup). The Yoredale Group in and fringing the East Irish Sea is underlain by the Clywd Limestone Group (Carboniferous Limestone Supergroup). In each instance the boundary is defined by the incoming of limestone facies over the mudstones and sandstones of the Yoredale Group.

Upper boundary

The Yoredale Group is unconformably overlain by the Bowland Shale Formation in north of Skipton. East of the Isle of Man (offshore) the group is unconformably overlain by Permian aged strata (Figure 6).

Age

Asbian – Yeadonian (late Visean – late Namurian; late Visean – mid Bashkirian)

2.5 CRAVEN GROUP

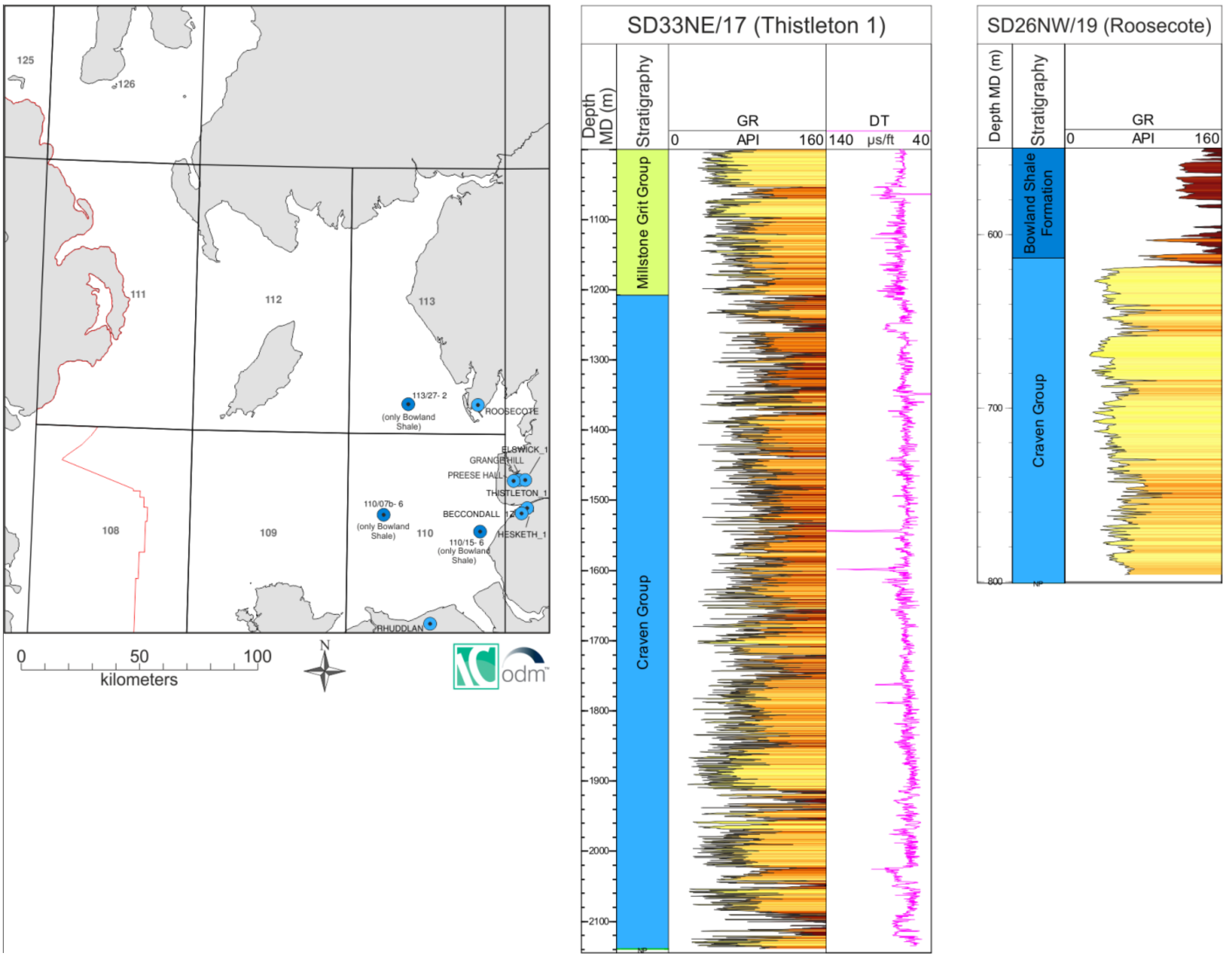

Figure 7 Distribution of the wells where the Craven Group has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Craven Group is here used as proposed by Waters et al. (2007). The Craven Group is composed of the Hodder Mudstone Formation, Pendleside Limestone Formation and the Bowland Shale Formation. The Bowland Shale Formation is additionally described in a section below.

Previous name

Previous names include the Gronant Group, Mallardale Shales, Worston Shale Group, Bowland Shale Group, Dyserth Limestone Group, and in offshore areas, the Bisat Group and Garwood Group (Jackson and Johnson, 1996).

Geological extent

Onshore the Group is present in the Craven Basin, between Clitheroe and Skipton; northeast Wales and the East Midlands. The unit is not observed in the East Irish Sea apart from in wells 110/07b-6, 110/15-6 and 113/27-2 but is interpreted on seismic (Pharaoh et al., 2016a) and in palaeogeographic reconstructions (section 5 below, inferred across southern and central parts of the East Irish Sea and Quad 109 areas).

Lithology

The unit is dominated by mudstones and siltstones (variably calcareous), sandstones, limestones and chert. Limestones includes packstones, floatstones, grainstones, wackestones as well as mudstone lithoclast breccias and 'boulder beds'. Some local zones of silicification and dolomitisation can be common, as well as localised gravity-driven slump deposits (Gawthorpe and Clemmey, 1985). The formations of Craven Group are typically defined by the variation in the abundance of mudstone and limestone, the dark organic mudstone-dominated succession of the Bowland Shale Formation described separately below.

Key wells

The Craven Group is interpreted in Roosecote (800.88 – 613.31 m), Thistleton 1 (2139.7 – 1207.6 m), Preese Hall 1 (2773.7 – 2743.2 m), Hesketh 1 (1295.4 – 660.46 m), Becconsall (3200.4 – 2385.6 m), Elswick 1 (1615.44 – 1250 m) and Rhuddlan (521.2 – 480 m). The thickest succession on the Craven Group is found in Thistleton 1 borehole (SD33NE/17); penetrating ~900 m (Figure 7). The gamma and sonic responses to this well also record a significant amount of heterogeneity borne from the variable lithological composition of the group. The age of the Craven Group is not constrained in this borehole but regionally in North Wales is Pendleian to Marsdenian (Davies et al. 2004). Where the Craven Group is overlain by the Bowland Shale Formation (also part of the Craven Group though differentiated here), as in Roosecote (SD26NW/19) the response is notably different. Below 613 m the Craven Group comprises interbedded dark grey, locally cherty limestones and dark grey mudstone partings (the Roosecote Limestone of Rose and Dunham, 1977), contrasting strongly with the argillaceous higher gamma facies of the Bowland Shale formation (Roosecote).

Lower boundary

The Craven Group is unconformably underlain in northeast Wales by the Clwyd Limestone Group (Carboniferous Limestone Supergroup). A sharp boundary is marked by a change from the Craven Group predominately mudstones, into the predominantly limestone facies of the Clwyd Limestone Group.

Upper boundary

The top of the group is defined by the base of the Millstone Grit Group, which is highly diachronous, ranging from Pendleian in age in the north to Yeadonian age. The boundary is taken at the top where dark grey mudstones cease to be predominate over the sandier and lighter colour facies of the Millstone Grit Group.

Age

Chadian – Yeadonian (early Visean – late Namurian; early Visean – mid Bashkirian)

2.6 BOWLAND SHALE FORMATION

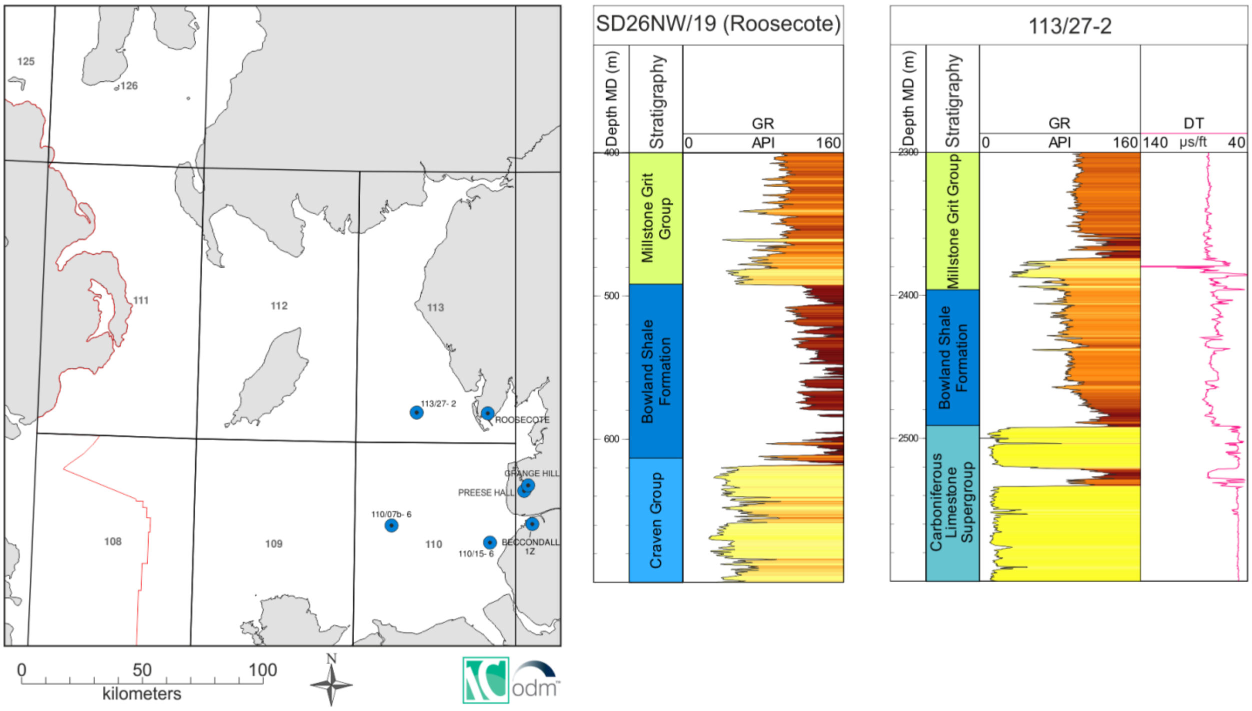

Figure 8 Distribution of the wells where the Bowland Shale Formation (Craven Group) has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Bowland Shale Formation is here used as defined by Waters et al. (2009) and with modifications for the Isle of Man by Dean et al. (2011).

Previous names

Previous names include the Cawdor Group, Edale Shale Group, Halkyn Formation, Holywell Shale, Lower Bowland Shale, Upper Bowland Shale, Edale Shale Group, Holywell Shale Formation, and offshore the Bisat Group and Garwood Group (Jackson and Johnson, 1996).

Geological extent

The formation is found in central and northern England, North Wales and the Isle of Man. Offshore it is interpreted to be present across southern and central parts of the East Irish Sea and Quad 109 areas (see section 5).

Lithology

Dark-grey, fissile and blocky mudstones and claystones, weakly calcareous are characteristic. Some subordinate sequences of interbedded carbonates, sandstones, ironstones are observed. The formation shows some facies variability associated with its geographical extent. In the Furness (south Cumbria) and Settle (North Yorkshire) areas the formation comprises thick-bedded, blocky to sub-fissile, dark grey and black, organic-rich mudstone, with subordinate beds of dark grey siltstone, sandstone and pale brown dolomitic limestone; some marine bands characterised by high gamma values are also present. The formation shows an upwards decrease in carbonate turbidites and an increase in siliciclastic sandstone turbidites (Arthurton et al., 1988). In the south

Isle of Man, the Bowland Shale Formation includes black claystone with localised deposition of carbonate turbidites, debris flows, olistoliths, volcaniclastic deposits and lavas (Chadwick et al., 2001; Dickson et al., 1987). Data is not available offshore to define in detail the character there.

Key wells

The Bowland Shale Formation is penetrated in 110/07b-6 (2482 – 1978 m), 110/15-6 (1885 – 1844 m), 113/27-2 (2491 – 2396 m), Roosecote (613.31 – 491.7 m), Grange Hill (3284.2 – 2186.9 m), Preese Hall (2743.2 – 1981.2 m), Becconsall (2385.6 – 2051.3 m). The Roosecote borehole (SD26NW/19) penetrates a complete succession of the Bowland Shale Formation (Craven Group). The gamma response to this borehole shows the typical high gamma responses associated with the highly argillaceous formation, with low gamma peaks coinciding with thin carbonate and siliceous turbidites. The presence of the diagnostic goniatites, coincident with gamma peaks suggest that the Cravenoceras malhamense Marine Band ($E_{1c}1$) is present at 553.95 m and from 521.95 to 529.00 m and that the thin limestone at 605 m coincides with the level of the Cravenoceras leion Marine Band (Rose and Dunham, 1977). Well 113/27-2 shows an example of the Bowland Shale Formation defined by a basal high gamma succession with a 'bell'-shaped wireline log profile (Figure 8), interpreted as a broadly upward-coarsening delta slope facies which prograded across the hemipelagic mudstone succession. The delta slope mudstones differ from the underlying basinal mudstones in that they are paler grey less pyritic, more silty and coarsely laminated and with some ironstones (Jackson and Johnson, 1996). The Bowland Shale Formation in 110/07b-6 is distinct in that it comprises a low gamma succession with the dominant component of light to dark grey, dolomitic, locally argillaceous limestone, interbedded with medium to dark grey or black, pyritic, locally dolomitic or calcareous claystone grading to siltstone and chert. The top of the formation is faulted in this borehole. The biostratigraphical evidence of Arnsbergian age below 2100 m (TK Biozone) and Pendleian (NC Biozone) from 2451-2482 m, along with the description of the background claystones as locally black and pyritic suggests an attribution to the Bowland Shale Formation is correct, but the dominance of carbonate facies contrasts in such a young interval has no equivalent onshore.

The Bowland Shale Formation in the Grange Hill Borehole shows common thin to thick beds of limestone. The more calcareous development with greater proportion of limestone, typically medium or dark grey, which occurs below c. 2800 m is considered to broadly equate with the Visean part of the succession. The thin limestones from the overlying mudstone-dominated succession are typically white. A comparable relationship is evident in the Preese Hall Borehole, with the transition occurring at c. 2500 m

In all examples the Bowland Shale Formation is overlain by the Millstone Grit Group. The boundary between the two is often defined by a thin low gamma spike that represents a coarse-grained sandstone prograding delta system (best seen in Well 113/27-2).

Lower boundary

The Bowland Shale Formation is typically underlain conformably by other formations of the Craven Group, notably onshore in the Craven Basin by the carbonate turbidites of the Pendleside Limestone Formation. Locally, in well 113/27-2 (Figure 8) the boundary is taken at the incoming of the underlying limestones of the Great Scar Limestone Group (Carboniferous Limestone Supergroup), which unconformably underlies the Bowland Shale Formation.

Upper boundary

The Bowland Shale Formation is conformably overlain by the Millstone Grit Group. The boundary is defined by the predominance of dark mudstones of the Bowland Shale Formation under the cyclic siliceous sequences of the Millstone Grit Group.

Age

Asbian – Yeadonian (late Visean – late Namurian; late Visean – mid Bashkirian)

2.7 MILLSTONE GRIT GROUP

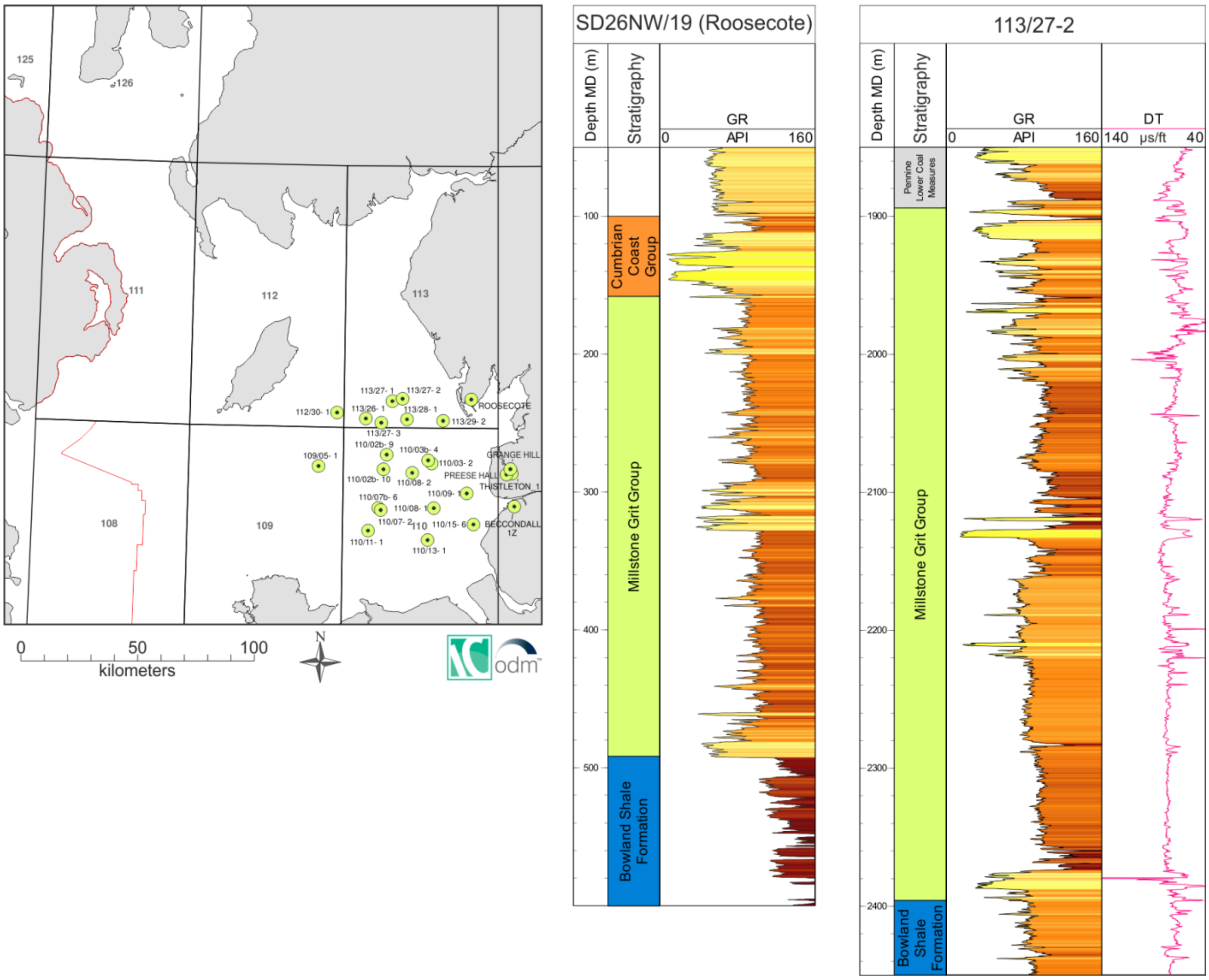

Figure 9 Distribution of the wells where the Millstone Grit Group has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Millstone Grit Group is here used as proposed by Waters et al. (2007). Onshore, in the Craven Basin of Lancashire and Yorkshire it comprises in ascending order; the Pendleton, Silsden, Samlesbury, Hebden, Marsden, and Rossendale formations. In north Wales a protoquartzitic sandstone-dominated succession, sourced from the south, is identified as the Cefn-y-fedw Sandstone Formation (Waters et al., 2009). An equivalent southerly sourced protoquartzitic succession seen in the North Staffordshire and the Widmerpool basins is termed the Morridge Formation (Waters et al., 2009; Morton et al., 2014).

Previous names

Previously the Millstone Grit Group has been called the Shale Group, Millstone Grit Formation, Millstone Grit, and offshore, the Bisat Group (Jackson and Johnson, 1996).

Geological extent

The Millstone Grit Group has wide geographical extent across northern and central England. Offshore, the group is limited to the East Irish Sea and eastern part Quad 109 (principally block 110) where is it proven in numerous wells (Figure 9) and picked on seismic (Pharaoh et al., 2016a). The Passage Formation of the Clackmannan Group, represents an equivalent facies present within the Midland Valley of Scotland and inferred to extend offshore into the Firth of Clyde.

Lithology

The group is typified by cyclic successions of quartz-feldspathic sandstone, grey mudstone, thin coal and prominent seatearths; resulting from deposition by repeated progradational deltas commonly exhibiting an upwards coarsening character. The heterolithic succession is characterised by the commonly coarse-grained nature of the sandstone (formerly referred to as grit), typically an arkosic or sub-arkosic arenite throughout the northern part of the onshore Central Pennine Sub-basin (including Lancashire and Yorkshire) and the youngest strata elsewhere in the southern part of the basin, with protoquartzitic arenites forming the older strata here (Cefn-y-fedw Sandstone and Morridge formations). Marine bands are common, representing discrete flooding events. These consist typically of dark grey to black, calcareous, shaly mudstone about 0.5 m, but ranging up to 15 m thick. Distinct ammonoid fauna and the extensive correlation of the marine bands makes them of primary stratigraphical importance (Waters and Condon, 2012; Waters et al. 2011e).

Key wells

The Millstone Grit Group is penetrated in wells; 109/05-1 (1731 – 1264 m), 110/02b-10 (2541 – 2354 m), 110/02b-9 (3464 – 2980.98 m), 110/03-2 (2588 – 2394 m), 110/03b-4 (3537 – 3297.87 m), 110/07-2 (1496 – 1238 m), 110/07b-6 (1978 – 1440 m), 110/08-1 (1308 – 1000 m), 110/08-2 (3115 – 2758 m), 110/09-1 (2608 – 2490 m), 110/11-1 (4194 – 3508 m), 110/13-1 (2804 – 2521 m), 110/15-6 (1844 – 1722 m), 112/30-1 (1369 – 585 m), 113/26-1 (3694 – 3633 m), 113/27-1 (3238 – 3060 m), 113/27-2 (2396 – 1894 m), 113/27-3 (3006 – 2850 m), 113/28-1 (2530 – 2380 m), 113/29-2 (2451 – 2310 m), Roosecote (491.7 – 158.13 m), Thistleton 1 (1207.6 – 926.24 m), Grange Hill (2186.9 – 1040 m), Preese Hall (1981.2 – 1140 m), Becconsall (2051.3 – 1956.8 m).

The Roosecote borehole (SD26NW/19) typifies the gamma response expected for the Millstone Grit Group showing a variety of both low and moderate responses with ‘cleaner’ horizons occurring in a broadly cyclic stacked pattern. Cycles commonly commence with a basal high gamma peak associated with a marine band, with a 'bell'-shaped wireline log profile interpreted as a broadly upward-coarsening delta slope facies, capped by a low gamma sandstone. Cycle thicknesses are typically thicker in the lower part of the group and are typified by the presence of turbiditic successions. The upper part of the group is characterized either by an erratic or a locally spiky wireline log response, and commonly terminated by a single sandstone possessing upward-increasing gamma values (e.g. 113/27-2), or a multi-storey sandstone with mudstone partings (e.g. Liverpool Bay 1, 110/2b-10; Jackson and Johnson, 1996). Thin low gamma and very low velocity coals occur sparsely (e.g. Liverpool Bay 1, 113/27-2) and in some wells, sandstones are thicker and more numerous (Jackson and Johnson, 1996). Well 109/05-1 is notable for the presence of relatively thick and closely spaced coal seams within Yeadonian strata of the Millstone Grit Group between 1423 and 1469 m.

Lower boundary

The conformable base is with the underlying Craven Group (e.g. Thistleton 1), though this boundary is proved in few offshore wells. The boundary is commonly taken at the base of the first thick sandstone within a run of thick sandstones, overlying the thick dark mudstone-dominated succession of the Craven Group.

Upper boundary

The group is conformably overlain by the Pennine Lower Coal Measures Formation. Onshore, the boundary is taken at the base of the Subcrenatum Marine Band, although offshore this marine band is not recognised definitively. Hence offshore, it is inferred within an interval dated by spores as Yeadonian-Langsettian at the base of a high gamma mudstone spike, which is inferred to be the Subcrenatum Marine Band (e.g. 113/27-2, 112/30-1), or at the base of a thicker mudstone interval of upward-decreasing gamma (e.g. 110/2b-10; Jackson and Johnson, 1996). The marine band directly overlies a thin, low gamma, low velocity coal spike (e.g. 112/30-1 and 110/2b-10), or in its absence, a low gamma channel sandstone (inferred to be an equivalent of the Rough Rock, e.g. 113/27-2) which commonly displays upward-increasing gamma values and argillaceous partings (e.g. Liverpool Bay 1; Jackson and Johnson, 1996). Where the marine band is not visible, the bottom of the lowermost coal-bearing sequence of the Pennine Lower Coal Measures Formation is used as the boundary. In the periphery of the Pennine Basin, especially in North Wales and north Cumbria, the base top of the Millstone Grit Group is marked by an unconformity.

Age

Pendleian – Yeadonian (Namurian; Serpukhovian – Bashkirian)

2.8 PENNINE COAL MEASURES GROUP

The 'Coal Measures' have historically had a chronostratigraphical name synonymous with Westphalian plus Stephanian strata. However, the name was redefined lithostratigraphically, to describe the main body of coal-bearing strata in the Westphalian succession, which in the Pennine Basin, extending across central and northern England and North Wales (and adjacent offshore areas) is termed the Pennine Coal Measures Group (Waters et al., 2007). Within the Midland Valley of Scotland, the equivalent unit, but with formations distinctively different boundary definitions, is termed the Scottish Coal Measures Group (Dean et al., 2011). The Pennine Coal Measures Group comprises in ascending order: Pennine Lower Coal Measures, Pennine Middle Coal Measures and Pennine Upper Coal Measures formations, described separately below.

The Pennine Coal Measures Group is interpreted at a group level in wells where there is insufficient information to provide formational level sub-divisions. This undifferentiated group is sometimes used for the entire group (all three constituent formations), or on occasion to signify only two of the three formations, e.g. 110/11-1 where the undifferentiated Pennine Coal Measures Group is used in place of the Pennine Upper and Middle Coal Measures formations, whilst the Pennine Lower Coal Measures Formation is recognised at formational level. The lack of subdivision is a consequence of the absence of information on diagnostic marine bands, the criteria by which the formational subdivision is based. This is sometimes compounded by instances where the Pennine Coal Measures Group is unconformably overlain by Permian strata; in such instances the level of erosion can remove some of the more diagnostic coal seams and marine bands.

2.8.1 Pennine Lower Coal Measures Formation

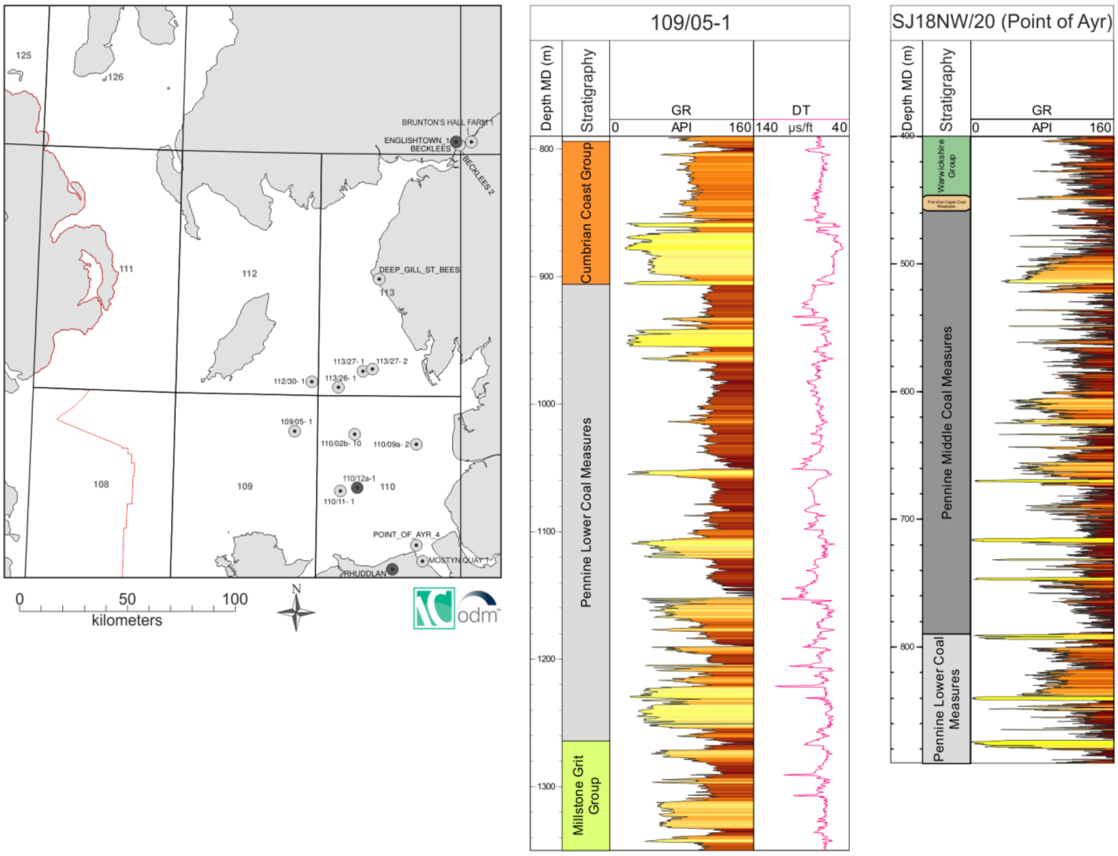

Figure 10 Distribution of the wells where the Pennine Lower Coal Measures Formation (Pennine Coal Measures Group) has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Lower Coal Measures was first defined by Stubblefield and Trotter (1957), but this report uses the Pennine Lower Coal Measures Formation (Pennine Coal Measures Group) as defined by Waters et al. (2009).

Previous names

Previous names include the Grey Measures of Yorkshire and Nottingham, Lower Coal Measures, and offshore the Kidston Group (Jackson and Johnson, 1996).

Geological extent

The unit is widespread across central and northern England, North Wales, north of the Isle of Man. The offshore extent proven in wells and by seismic interpretation (Pharaoh et al., 2016a) is across parts of the East Irish Sea, northern part of Quad 109 and southern part of the Solway Basin, although is extensively removed beneath the Variscan Unconformity across these areas.

Lithology

The unit comprises interbedded grey mudstone, siltstone and pale grey sandstone, commonly with mudstones containing marine fossils in the lower part, and more numerous and thicker coal seams in the upper part. The sandstones include both micaceous and green, weakly micaceous sandstones. In the subsurface of the East Midlands, coal and oil exploration has revealed alkali basalt lavas and tuffs, limited to the Pennine Lower Coal Measures Formation. The formation is primarily grey in colour though secondary reddening is present; especially where the formation is overlain by unconformities.

Key wells

The Pennine Lower Coal Measures Formation is penetrated in wells: 109/05-1 (1264 – 906 m), 110/02b-10 (2354 – 2166 m), 110/09a-2 (1600 – 1391 m), 110/11-1 (3508 – 3420 m), 112/30-1 (585 – 540 m), 113/26-1 (3633 – 3344 m), 113/27-1 (3060 – 2918 m), 113/27-2 (1894 – 1778 m), Deep Gill St Bees (500 – 470 m), Becklees (1350.4 – 1248 m), Becklees 2 (1386 – 1237 m), Bruntons Hill Farm (1005 – 299 m), Point of Ayr (891 – 790 m), Mostyn Quay 1 (243.8 – 0 m).

Well 109/05-1 shows a thick cyclic succession of the Pennine Lower Coal Measures Formation (Figure 10), with gamma and sonic responses resulting from the cyclic depositional character present through, and characteristic of, the deposition of all of the Pennine Coal Measures Group. The formation 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 (e.g. Liverpool Bay 1; Jackson and Johnson, 1996). The upward-coarsening cyclothems exhibit a 'vase-shaped' motif; where an upward-coarsening unit is overlain by an upward-fining fluvially-dominated unit, an 'egg-shaped' wireline log response is displayed (Jackson and Johnson, 1996). The overall log patterns are sporadically interrupted by distinctive, low gamma (30-60 API units), very low density, very low velocity, high resistivity, spikes indicative of coals (e.g. Liverpool Bay 1; Jackson and Johnson, 1996). Scarce, high gamma (90-110 API units) spikes typically represent marine bands and some non-marine mussel-bands (Jackson and Johnson, 1996). The sandstones show considerable variation in wireline log character, including 'box-car' motifs in thick, distributary channel sandstones (e.g. 112/30-1; Jackson and Johnson, 1996).

In wells 110/12a-1, Englishtown 1 (NY37SW/6) and Rhuddlan (SJ07NW/28) it has not been possible to discriminate the Pennine Lower Coal Measures Formation from the rest of the group. The lack of formation subdivision of the group in these instances relates to difficulty in recognising the distinction between strata of Langsettian and Duckmantian age through absence of adequate biostratigraphical control.

Lower boundary

The Pennine Lower Coal Measures Formation is typically underlain conformably by the Rossendale Formation (Millstone Grit Group). The boundary is taken at the fissile mudstone of the Subcrenatum Marine Band. In the periphery of the Pennine Basin, especially in North Wales and north Cumbria, the base top of the Millstone Grit Group is marked by an unconformity. Here, where the Subcrenatum Band is not recognised, the boundary is taken at the base of the lowest coal-bearing sequence.

Upper boundary

The unit is regionally overlain conformably by the Pennine Middle Coal Measures Formation. The boundary is taken at the base of the Vanderbeckei Marine Band.

Age

Langsettian (Westphalian A; Bashkirian)

2.8.2 Pennine Middle Coal Measures Formation

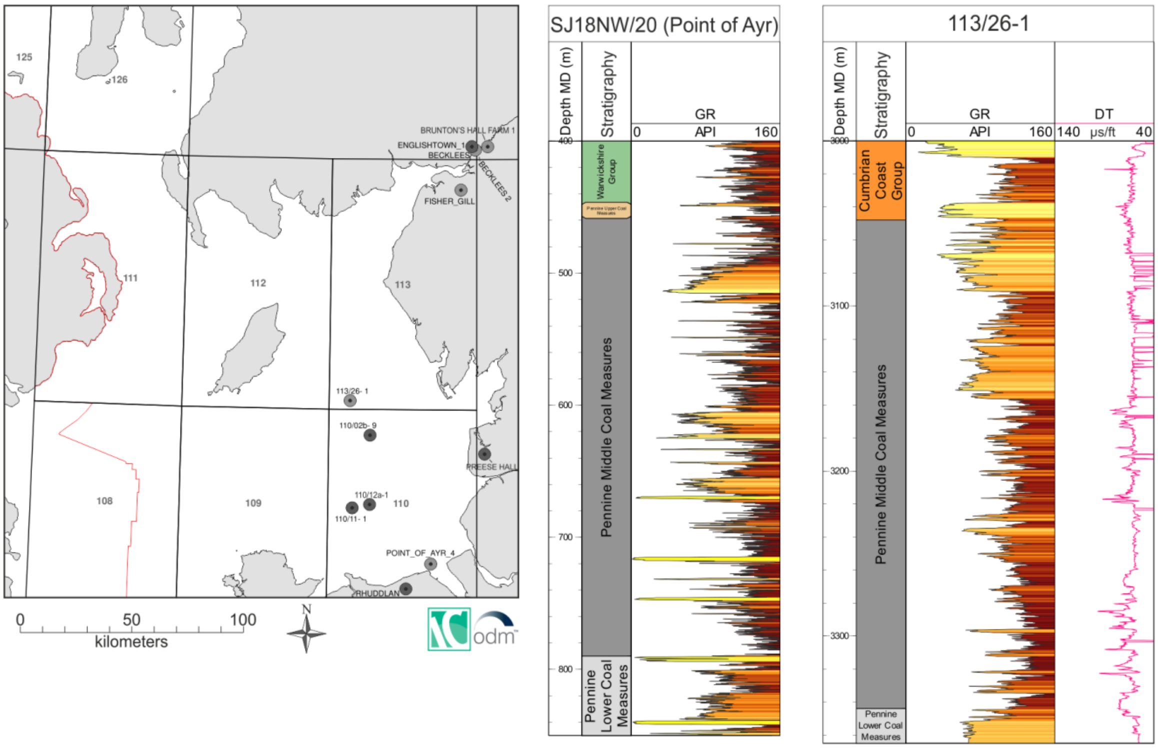

Figure 11 Distribution of the wells where the Pennine Middle Coal Measures Formation (Pennine Coal Measures Group) has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Middle Coal Measures was first defined by Stubblefield and Trotter (1957), but this report uses the Pennine Middle Coal Measures Formation (Pennine Coal Measures Group) as defined by Waters et al. (2009).

Previous names

Previous names include the Grey Measures of Yorkshire and Nottingham, Middle Coal Measures Formation, and offshore, the Kidston Group (Jackson and Johnson, 1996)

Geological extent

The unit is proven onshore in North Wales and central and northern England. Offshore the extent is proven by wells in the western and southern parts of the East Irish Sea. It is extensively removed beneath the Variscan Unconformity across the offshore areas (see Pharaoh et al. 2016b).

Lithology

The strata comprise interbedded grey mudstone, siltstone, pale grey sandstone and commonly coal seams, with a bed of mudstone containing marine fossils at the base, and several such marine fossil-bearing mudstones in the upper half of the unit. In the northern England, the sandstones are generally thicker and coarser than is typical of the Coal Measures elsewhere. The formation is primarily grey in colour though secondary reddening is present; especially where the formation is overlain by unconformities.

Key wells

The Pennine Middle Coal Measures is present in wells: 11/26-1 (3344 – 3048 m), Fisher Gill (1168 – 861 m), Becklees (1248 – 944.1 m), Becklees 2 (1237 – 290 m), Bruntons Hill Farm (299 – 105 m), and Point of Ayr (790 – 457 m).

Wells 113/26-1 and Point of Ayr (SJ18NW/20) both show the typical cyclic gamma responses expected from the cyclic progradation of minor deltas. The sharp lower gamma responses likely correspond to the clean sandstone bodies that commonly underlie coal seams (if present). In the offshore, only well 113/26-1 is recognised as having the Pennine Middle Coal Measures Formation present. This well has a number of thin coal seams throughout the formation and these are characterised by sharp reductions in sonic responses.

Lower boundary

The unit is conformably underlain by the Pennine Lower Coal Measures Formation. The boundary is defined at the base of the Vanderbeckei Marine Band.

Upper boundary

The unit is conformably overlain by the Pennine Upper Coal Measures Formation. The boundary is defined by the top of the Cambriense Marine Band. Where the Pennine Upper Coal Measures Formation is removed, it is bounded by an unconformity at the base of Permian strata (see section 4).

Age

Duckmantian – Bolsovian (Westphalian B – Westphalian C; Moscovian)

2.8.3 Pennine Upper Coal Measures Formation

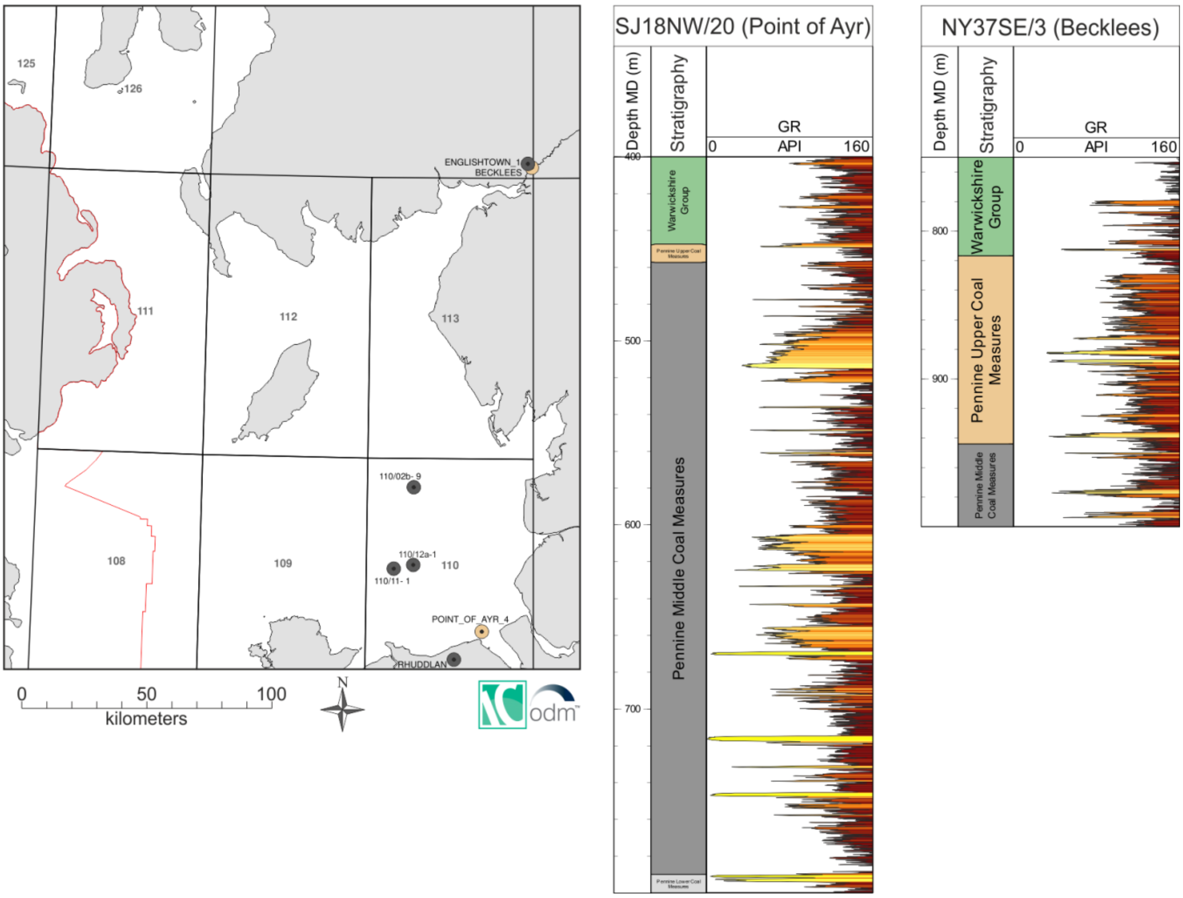

Figure 12 Distribution of the wells (in beige) where the Pennine Upper Coal Measures Formation (Pennine Coal Measures Group) has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit. Offshore wells (grey) show Pennine Coal Measures undifferentiated.

Name

The Upper Coal Measures was first defined by Stubblefield and Trotter (1957), but this report uses the Pennine Upper Coal Measures Formation (Pennine Coal Measures Group) as defined by Waters et al. (2009).

Previous names

Previous names include the Upper Coal Measures Formation, and offshore, the Kidston Group (Jackson and Johnson, 1996).

Geological extent

The unit extends onshore in central and northern England and North Wales. Offshore the extent is proven by wells in the western and southern parts of the East Irish Sea. It is extensively removed beneath the Variscan Unconformity across the offshore areas (see Pharaoh et al. 2016b and subcrop map). The near equivalent unit in the onshore area of central Ayrshire (Scottish Upper Coal Measures Formation) includes cyclic sandstone, siltstone and mudstone successions, reddish brown or purple, though to be largely the result of secondary reddening, though some may be primary reddening.

Lithology

The strata comprise interbeds of mudstone, siltstone, pale grey sandstone and relatively common coal seams (often) relatively thin. Marine mudstone layers (marine bands) are atypical for the entire group and none are found within the Pennine Upper Coal Measures which entirely lacks the presence of marine fossils of any type. The succession is primarily grey in colour though secondary reddening is common in upper portions towards the unconformity that marks the top of the formation in the East Irish Sea.

Key wells

The Pennine Upper Coal Measures Formation is only interpreted in wells Becklees (944.1 – 816.8 m) and Point of Ayr (457 – 448 m).

The Pennine Upper Coal Measures is often locally removed beneath the Variscan unconformity and only readily identifiable in onshore boreholes (Becklees; NY37SE/3) or those immediately proximal to coastline (Point of Ayr; SJ18NW/20) (Figure 12). The gamma responses for this formation are comparable to the rest of the Pennine Coal Measures Group, though the cyclicity typical of the group as a whole is not observed.

The Pennine Upper Coal Measures Formation is not identified in offshore wells. This absence is related to the local removal of the formation via erosion. Wells 110/2b-9, 110/11-1 and 110/12a-1 all show the Pennine Coal Measures Group (undifferentiated) overlain unconformably by Permian aged strata.

Lower boundary

The unit is conformably underlain by the Pennine Middle Coal Measures Formation. The boundary is taken at the top of the Cambriense Marine Band.

Upper boundary

A conformable boundary with the overlying Warwickshire Group is taken where primary red-coloured mudstones become predominant over grey mudstones. Where the Warwickshire Group is absent the Pennine Upper Coal Measures is bounded by an unconformity at the base of Permian strata (Variscan Unconformity), note that in such instances erosion associated with the unconformity may have removed large portions of the formation.

Age

Bolsovian – Asturian (Westphalian C – Westphalian D; Moscovian)

2.9 WARWICKSHIRE GROUP

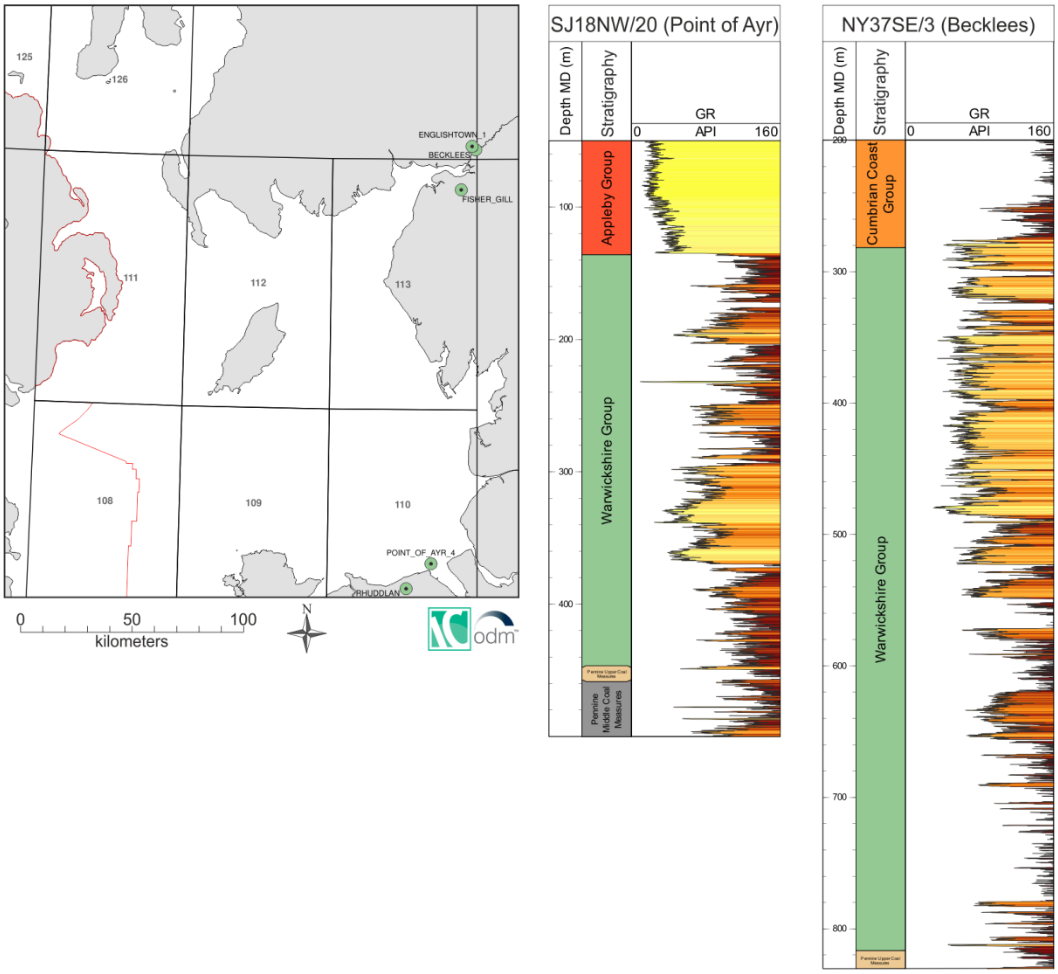

Figure 13 Distribution of the wells where the Warwickshire Group has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Warwickshire Group name was introduced by Powell et al. (2000) for Carboniferous strata above the Pennine Upper Coal Measures. The Warwickshire Group is composed of the Etruria Formation (Midlands, Lancashire, Yorkshire and North Wales), the Halesowen Formation (Pennine Basin, central England and North Wales), the Salop Formation (Staffordshire, Shropshire and Warwickshire), the Clent Formation (West Midlands), the Tile Hill Mudstone Formation (southern part of the Warwickshire Coalfield), the Whitehaven Sandstone Formation (west Cumbria) and Eskbank Wood, Canonbie Bridge Sandstone and Becklees Sandstone formations (north Cumbria).

Previous names

Previous names include the Ardwick Group (in Lancashire), Barren Measures Group, Red Measures.

Geological extent

The Warwickshire Group is proven onshore within the Pennine Basin in Staffordshire, Warwickshire, Shropshire, Lancashire, Nottingham and South Yorkshire and is found at crop in the Canonbie (Solway Basin) and Whitehaven areas. Offshore, the group is not definitively proved in wells and its offshore extent is mapped only on seismic data, present within the Eubonia Basin, northern Quad 109, west of Whitehaven-Workington in the Solway Basin and north of the North Wales coast (Pharaoh et al., 2016b and subcrop map). The common absence of an unconformity (as is observed onshore in the Canonbie Coalfield and much of the Flint Coalfield of North Wales) at the base of the group may in part result in difficulty discriminating this group from secondarily reddened Pennine Coal Measures and Millstone Grit groups. It is probable that the group was deposited across much of the East Irish Sea Basin, but was eroded during Late Carboniferous Variscan inversion.

Lithology

The onshore Warwickshire Group of North Wales and Cheshire Basin comprises predominantly red, brown, purple-grey and locally green-grey siltstones and mudstones (Etruria Formation and lower part of the Salop Formation). Sandstones, conglomerates are a common, though subordinate component of the Etruria Formation and a significant component of the upper part of the Salop Formation. Thick sandstones and subordinate thin limestones and coals occur interbedded with grey mudstone within the Halesowen Formation. Sandstones and conglomerates where locally present can be micaceous and/or contain sediment of volcaniclastic origin. Conglomeratic units may contain clasts of carboniferous limestones and chert. Siltstones and mudstones can locally show evidence of pedogenesis though coal seams are generally rare. In Shropshire and the West Midlands the group also contains limestones, some of which show sub-aerial exposure and subsequent pedogenesis. The amount of sandstone to mudstone and siltstones within constituent formations of the Warwickshire Group varies considerably.

Within the axis of the Solway Syncline, the Warwickshire Group is recognised, in ascending order, as the Eskbank Wood, Canonbie Bridge Sandstone and Becklees Sandstone formations (Jones et al., 2011; Dean et al., 2011), with a combined thickness of less than 700 m. The three formations are lithologically comparable to the formations from the type area of the Warwickshire Group. The group is considered to be removed by the unconformity at the base of the Permian succession immediately to the west of the syncline (Jones et al., 2011), but a presence offshore in the Solway Firth area, where seismic data is limited, is possible. In west Cumbria a distinct component of the Warwickshire Group is recognised. The Whitehaven Sandstone Formation, at least 280 m thick (Akhurst et al., 1997; Dean et al., 2011) is mainly a red to deep purple or purplish brown, cross-bedded, micaceous, medium- to coarse- grained sandstone.

Key wells

The Warwickshire Group is only identified in onshore wells: Fisher Gill (861 – 798 m), Becklees (816.8 – 281.7 m; Figure 13), Englishtown 1 (603 – 275.5 m), Rhuddlan (300 – 91 m) and Point of Ayr (448 – 136 m; Figure 13).

The unit is proven in the boreholes of Englishtown 1 (NY37SW/6) and Becklees (NY37SE3) in the Solway Basin and Point of Ayr (SJ18NW/20), North Wales, which show the highly variable gamma response indicative of the Warwickshire Group (Figure 13). However, within these responses successions of relatively high, moderate and low gamma can be delineated and likely reflect some of the constituent formations of the group.

Lower boundary

A gradational conformable base with the underlying Pennine Upper Coal Measures Formation (Pennine Coal Measures Group) is typically observed, both at the base of the Etruria Formation in the southern onshore margins of the region and the Eskbank Wood Formation within the Solway Basin. The boundary is commonly taken at the red mudstone directly above the Pennine Coal Measures Group. Locally, in Shropshire, Warwickshire and Lincolnshire the base of the group is an unconformity (Symon Unconformity; Powell et al., 2000). A prominent unconformity at the base of the Whitehaven Sandstone is proved offshore in the northern East Irish Sea Basin (Chadwick et al. 2001).

Upper boundary

The upper boundary is the Variscan Unconformity, with the strata of the Warwickshire Group overlain unconformably by Permian or younger strata, commonly the Cumbria Coast or Appleby Groups.

Age

Late Bolsovian – Early Permian (Moscovian – Cisuralian)

3 Permian

3.1 APPLEBY GROUP

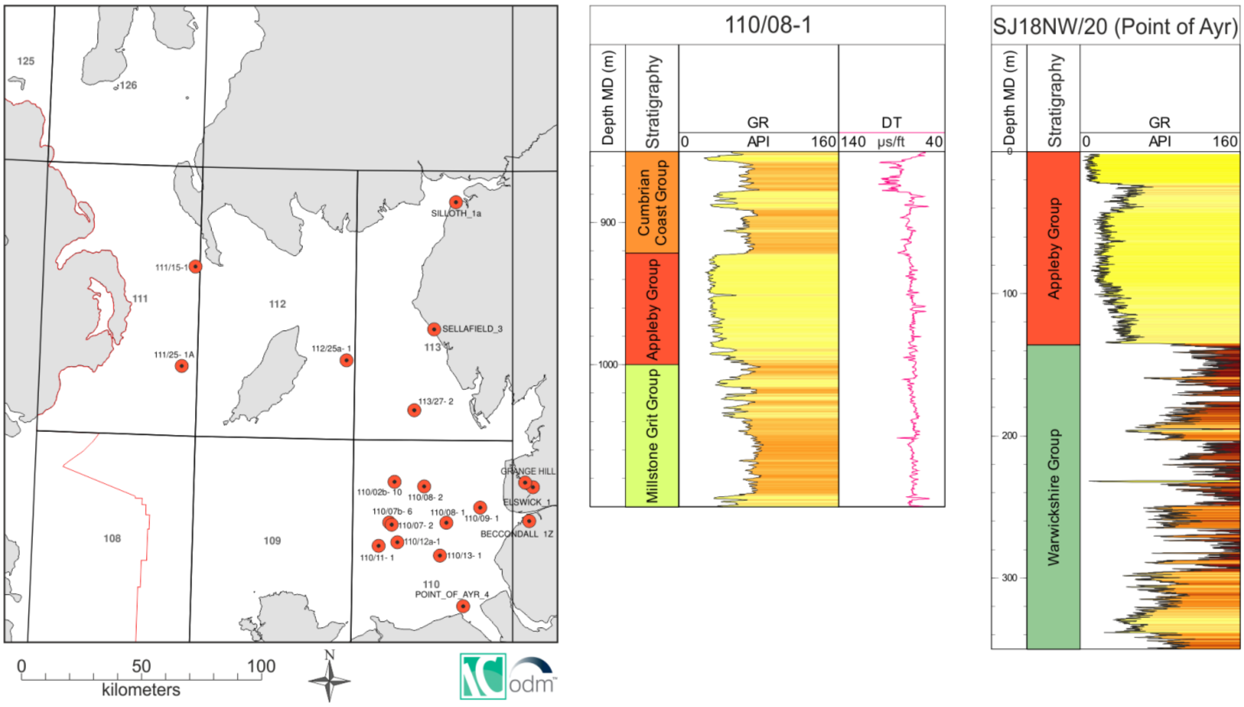

Figure 14 Distribution of the wells where the Appleby Group has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Appleby Group was introduced by Jackson and Johnson (1996). It includes component formations of the Brockram Formation (of the Vale of Eden and Cumbria), Collyhurst Sandstone Formation (of Lancashire and Cheshire) and Penrith Sandstone Formation (of the Eden Valley and Solway Basin).

Previous names

The group was not previously recognised by Smith et al. (1974). It is the equivalent of the Rotliegend Group of the North Sea.

Geological extent

The unit is present in the northern part of the Solway Basin, northern parts of Cheshire Basin and extending to at least the far west of the Isle of Man (Jackson et al., 1987). Offshore wells prove this group in the East Irish Sea Basin, Solway Basin and Manx-Peel Basin. The Appleby Group is not proven in the North Channel to Firth of Clyde.

Lithology

The strata comprise predominantly sandstone and breccia with a minor component of mudstone. Aeolian processes dominated during deposition of the Appleby Group, as a result the majority of sandstones have aeolian affinity and are characterised by a millet-seed texture and are frequently cross-bedded. The arrangement is commonly defined by a basal breccia, overlain by thick sequence of aeolian sandstones, culminating in an upper sequence of breccias.

Key wells

The Appleby Group is present in wells: 110/02b-10 (2121.14 – 2025 m), 110/07-2 (1238 – 1179 m), 110/07b-6 (1440 – 1274 m), 110/08-1 (1000 – 921.56 m), 110/08-2 (2758 – 2749 m), 110/09-1 (2490 2324 m), 110/11-1 (3158 – 2399 m), 110/12a-1 (2851 – 2088 m), 110/13-1 (2521 – 1714 m), 111/15-1 (1962 – 1943 m), 111/25-1a (1596 – 1525 m), 113/27-2 (1778 – 1735 m), Sellafield 3 (1473.82 – 1315.22 m), Silloth 1a (1311.9 – 933.3 m), Grange Hill (1040 – 950 m), Becconsall (1956.8 – 1619.3 m), Elswick 1 (1250 – 1038.8 m) and Point of Ayr (136 – 0 m).

The predominately clean sandstones and breccias of the Appleby Group lead to consistently low 'clean' gamma and relatively high and largely consistent sonic responses, as seen in wells 110/08-1 and Point of Ayr (Figure 14). This low gamma response is readily evident when the Appleby Group unconformably overlies Carboniferous aged formations. In such instances the gamma response of the Appleby Group often contrasts markedly from the generally more argillaceous Carboniferous strata, e.g. the Warwickshire Group as seen in Point of Ayr (Figure 14).

In Sellafield 3 (NY00SW/35) the Appleby Group is entirely represented by the Brockham Formation. The Brockham Formation in Sellafield 3 has an unusual and non-typical gamma response that is consistently high. The sonic response is however more typical of the regional group signature. The Brockham Formation is predominantly composed of breccias and lithic arenites. Clasts are dominantly angular and subangular volcanic clasts derived from the Borrowdale Volcanic Group with minor mono- and polycrystalline quartz, cherts and carbonate clasts (Strong et al., 1994). The formation can contains some interbedded ferruginous mudstones. The breccias are generally very poorly sorted ranging in size from silt to large pebbles. The lithic arenites are moderately sorted and commonly laminated.

Lower boundary

The unit is unconformable on and commonly overlies secondarily reddened Carboniferous sedimentary rocks. In well 110/02b-10 the Appleby Group is interpreted to be underlain by a post-Permian igneous intrusion. The typical clean gamma and high sonic response are slightly higher and lower (respectively) and this is likely resulting from a 'baked' margin adjacent to the intrusion.

Upper boundary

The unit is overlain by the Cumbria Coast Group with an interpreted minor unconformity (Jackson and Johnson, 1996). The boundary is defined where sandstone becomes subordinate to either mudstone, siltstone, carbonate or evaporites.

Age

An Early Permian age is inferred from lateral correlation with sequences in northeast England and northwest Europe, and from the stratigraphic relationships to the underlying Westphalian C and D deposits, and the overlying Late Permian deposits. The aeolian sandstone and upper breccia successions are believed to date from the later Early Permian (Smith and Taylor, 1992).

3.2 CUMBRIAN COAST GROUP

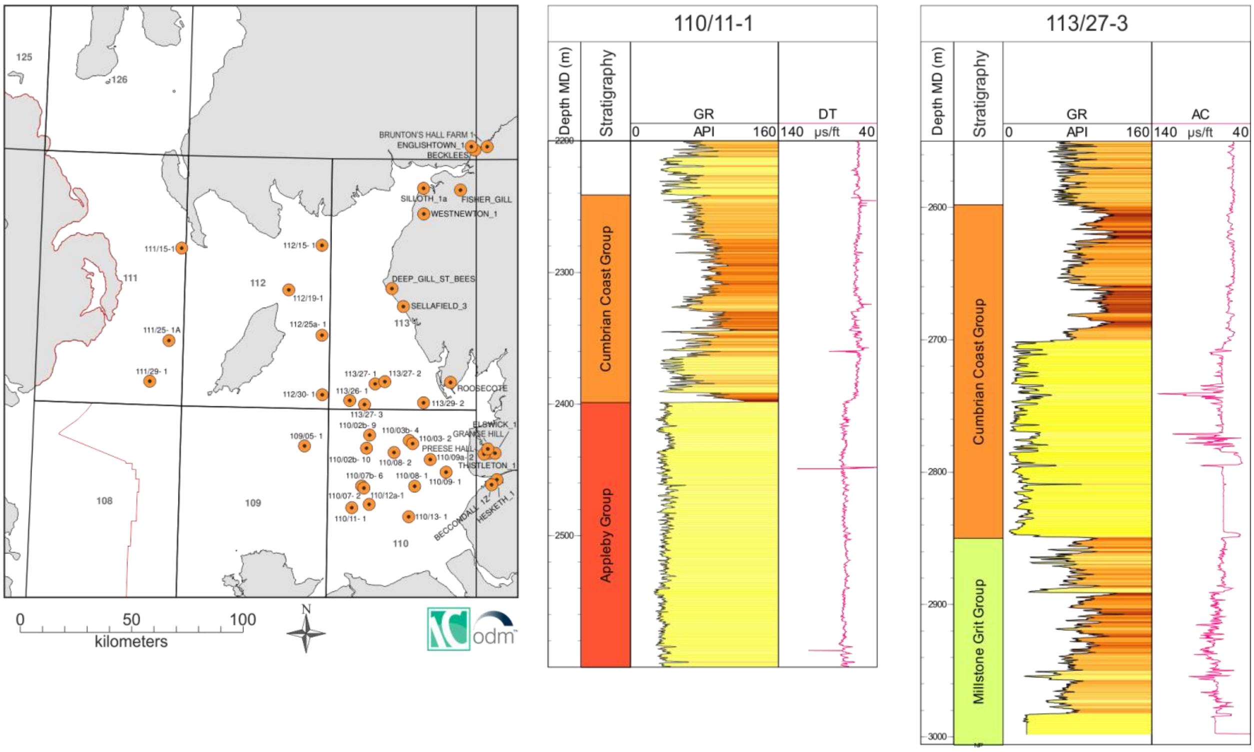

Figure 15 Distribution of the wells where the Cumbrian Coast Group has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Cumbrian Coast Group was introduced based on the Upper Permian strata of northwest England and southern Scotland (Jackson and Johnson, 1996; cf. Chadwick et al., 1995).

Constituent offshore formations

Manchester Marls Formation; Red calcareous mudstones and siltstones interbedded with thin fossiliferous limestones and dolomite present in the eastern and southern parts of the East Irish Sea and northen part of Quad 109. Can be locally green in colour, sandy in places and also contain pebbly or breccias. This formation has a typical thickness of 45 – 60 m.

Barrowmouth Mudstone Formation; Red-brown mudstones present in the northern and central parts of the East Irish Sea, lateral offshore equivalent of the onshore St Bees Shales.

St Bees Evaporite Formation; Primarily located in the north and central areas of the East Irish Sea the St Bees Evaporite Formation is characterised by thick sequence of evaporites (predominately halite). Comparatively, the onshore well penetrations of the formation comprise a condensed succession of interbedded dolomite and anhydrites (Arthurton and Hemingway, 1972).

Geological extent

The units are widespread in the East Irish Sea and bordering land areas west of the Pennines (i.e. the Bakevellia Sea Basin of Smith et al., 1974; Jackson et al., 1987).

Lithology

In the northern and central parts of the East Irish Sea, the Cumbrian Coast Group consists of thick evaporites (St Bees Evaporite Formation; Jackson et al., 1987), predominately halite, overlain by red-brown mudstones (Barrowmouth Mudstone Formation; Jackson and Johnson, 1996). The halites of the St Bees Evaporite Formation thin southwards in the East Irish Sea and pass laterally into dolomitic mudstones of the Manchester Marls Formation (Jackson and Johnson, 1996). Jackson and Johnson (1996) defined the sequence below the Barrowmouth Mudstone Formation based on the amount of the volumetric percentage of the group below the Barrowmouth Mudstone Formation, less than 40% equating to the Manchester Marl Formation and more than 40% interpreted as the St Bees Evaporites Formation.

Key wells

The Cumbria Coast Group is interpreted in wells: 109/05-1 (906 – 794 m), 110/02b-10 (2025 – 1969 m), 110/02b-9 (2448 – 2329 m), 110/03-2 (2394 – 2315 m), 110/03b-4 (2397.87 – 2991 m), 110/07-2 (1179 – 1074 m), 110/07b-6 (1274 – 1138 m), 110/08-1 (921.56 – 738 m), 110/08-2 (2749 – 2448 m), 110/09-1 (2324 – 2153 m), 110/09a-2 (1391 – 1213 m), 110/11-1 (2399 – 2241 m). 110/12a-1 (2088 – 1957 m), 110/13-1 (1814 – 1668 m), 111/15-1 (1943 – 1478 m), 111/25-1a (1525 – 1363 m), 111/29-1 (1096 – 1003 m), 112/15-1 (2349 – 2172 m), 112/19-1 (1882 – 1683 m), 112/25a-1 (2090 – 1762 m), 112/30-1 (540 – 467 m), 113/26-1 (3048 – 2634.51 m), 113/27-1 (2918 – 2723 m), 113/27-2 (1735 – 1707 m), 113/27-3 (2850 – 2598 m), 113/29-2 (2310 – 2025 m), Deep Gill St Bees (470 – 370 m), Sellafield 4 (1315.22 – 1133.98 m), Westnewton 2 (199.64 – 160 m), Silloth 1a (933.3 – 870.5 m), Fisher Gill (798 – 745 m), Becklees (281.7 – 0 m), Becklees 2 (209 – 0 m), Englishtown 1 (275.5 – 205 m), Roosecote (158.13 – 100 m), Thistleton 1 (926.24 – 818.95 m), Grange Hill (950 – 880.6 m), Preese Hall (1140 – 1030.2 m), Hesketh 1 (660.46 – 563.54 m), Becconsall 1z (1619.3 – 1463 m), and Elswick 1 (1038.8 – 836.9 m).

The spatial variability in lithological expression at the base of the Cumbria Coast Group creates a variety of geophysical responses. Well 113/27-3 (Figure 15) shows a relatively low gamma response likely relating to the evaporitic facies often seen in then north and central areas of the East Irish Sea. In contrast, in the southerly areas such as that illustrated by Well 110/11-1, indicate higher gamma responses resulting from the lateral transition of the group into more argillaceous facies of the Manchester Marls Formation. The range of responses to both gamma and sonic tests is best seen in Sellafield 3. The basal gamma low of the group in Sellafield 3 corresponds to the St Bees Evaporites Formation; a dolomite and anhydrite rich succession (Strong et al., 1994). The rest of the group is characterised by a comparatively slower sonic and higher gamma response resulting from the St Bees Shales Formation; a more argillaceous formation with subordinate sandstones, breccias and evaporites.

Lower boundary

The base of the Cumbria Coast is represented by an abrupt disconformity with the underlying Appleby Group (Jackson and Johnson, 1996), defined by the change from mudstone, siltstone or carbonates to the underlying sandstones of the Appleby Group. Where the Appleby Group is absent the Cumbria Coast Group sits unconformably on reddened Carboniferous strata.

Upper boundary

The top of the Cumbria Coast Group is taken at the sharp base of the sandstone-dominated succession of the Sherwood Sandstone Group, considered to represent a non-sequence boundary (Jackson and Johnson, 1996).

Age

Considered to be Late Permian to Early Triassic (Johnson et al., 1994).

4 Correlation Panels

The correlation panels illustrate the stratigraphic relationships and lithofacies variations of the Carboniferous rocks of the Irish Sea.

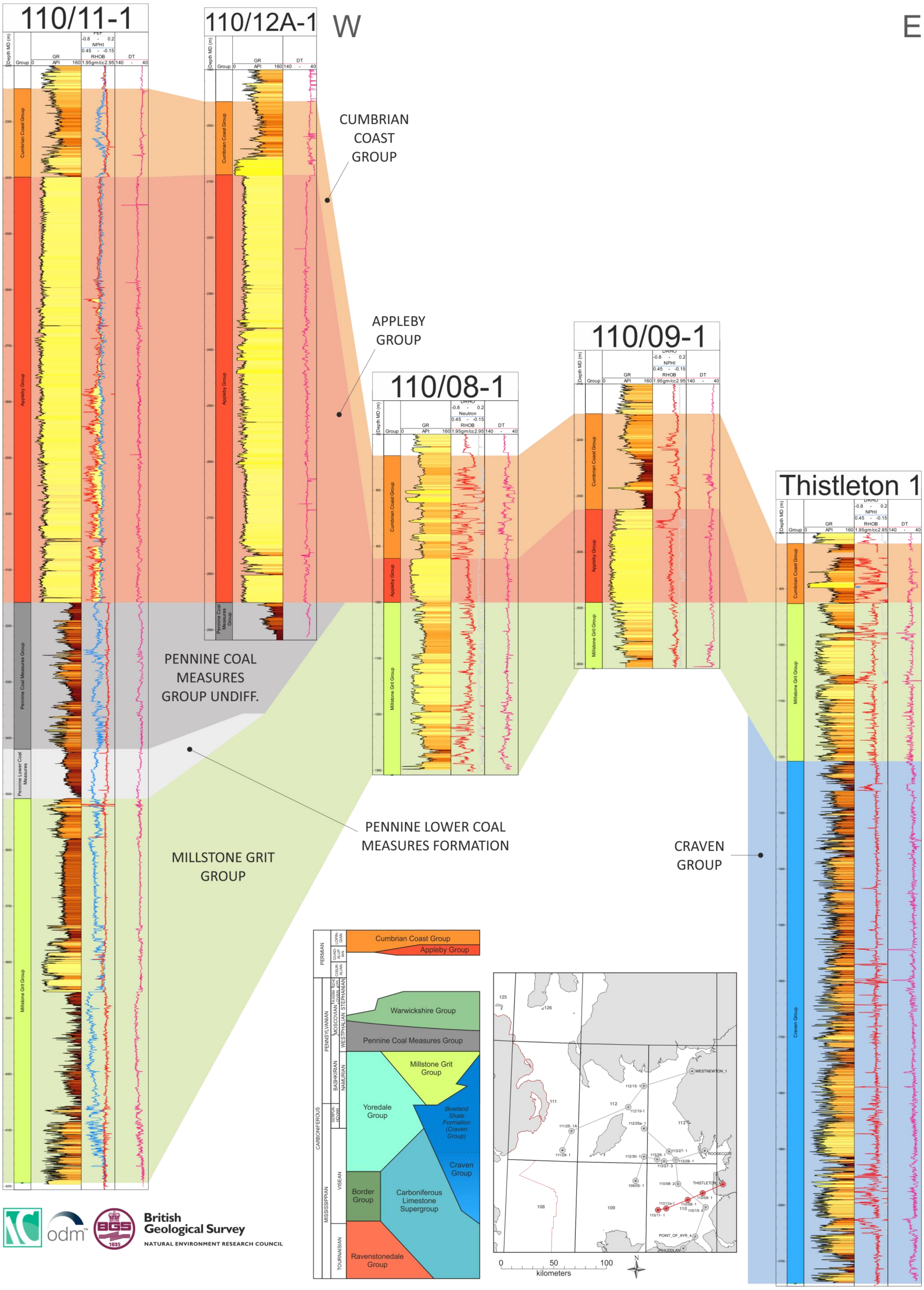

Figure 16 West to east correlation of the Carboniferous and Permian strata for the southern part of the East Irish Sea.

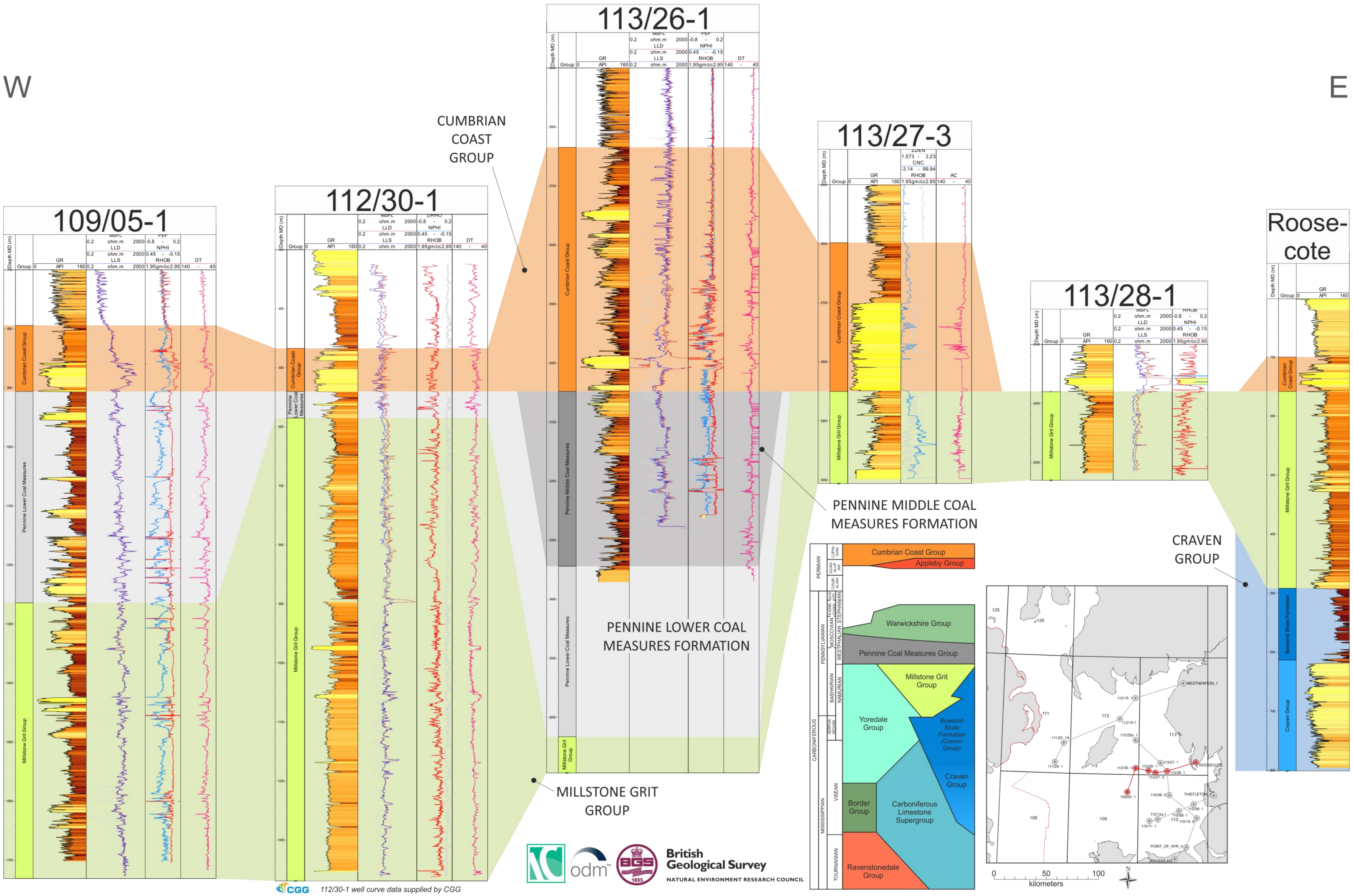

Figure 17 West to east correlation Carboniferous and Permian strata for the central part of the East Irish Sea.

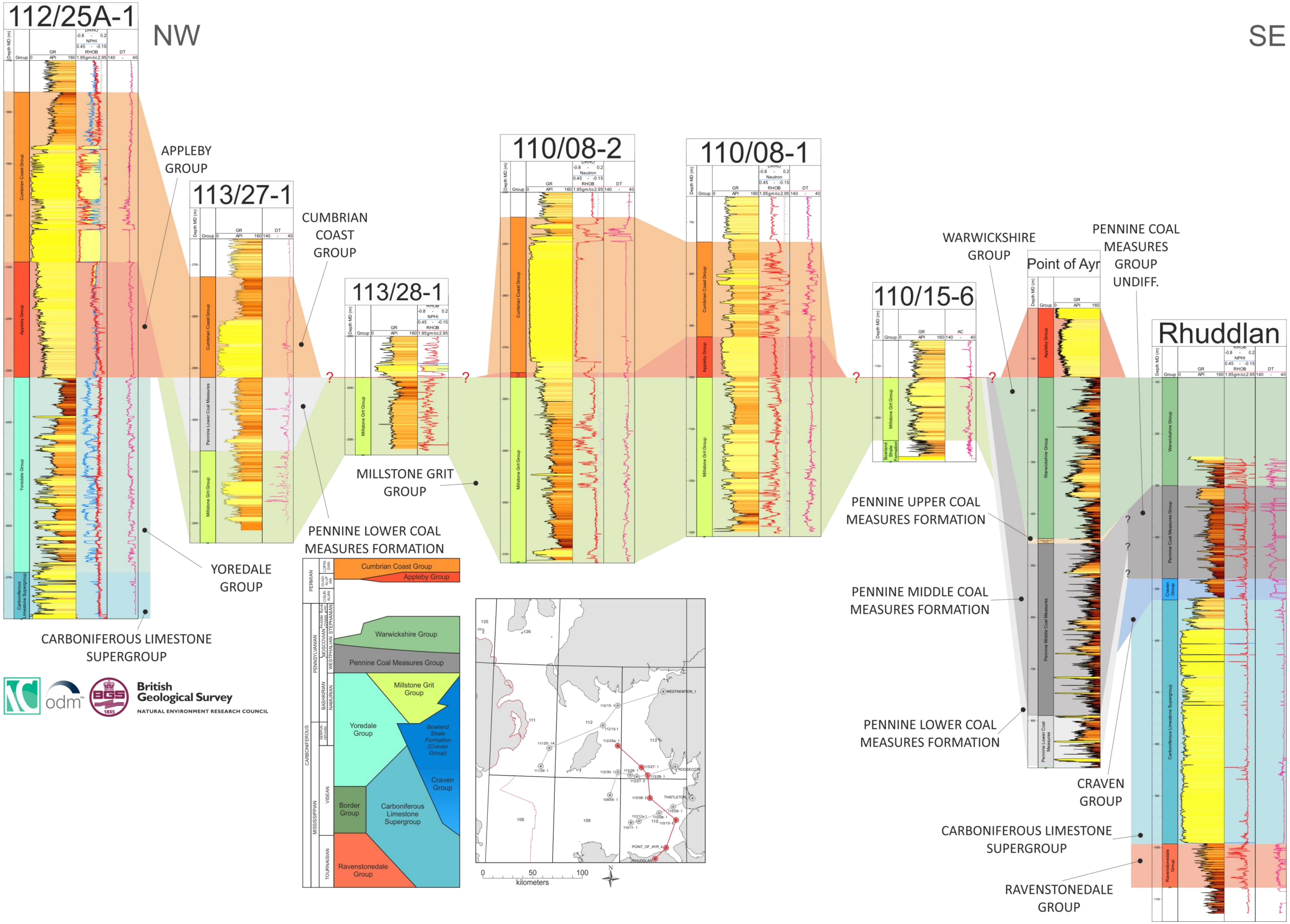

Figure 18 Northwest to southeast correlation of the Carboniferous and Permian Strata for the central and southern part of the East Irish Sea.

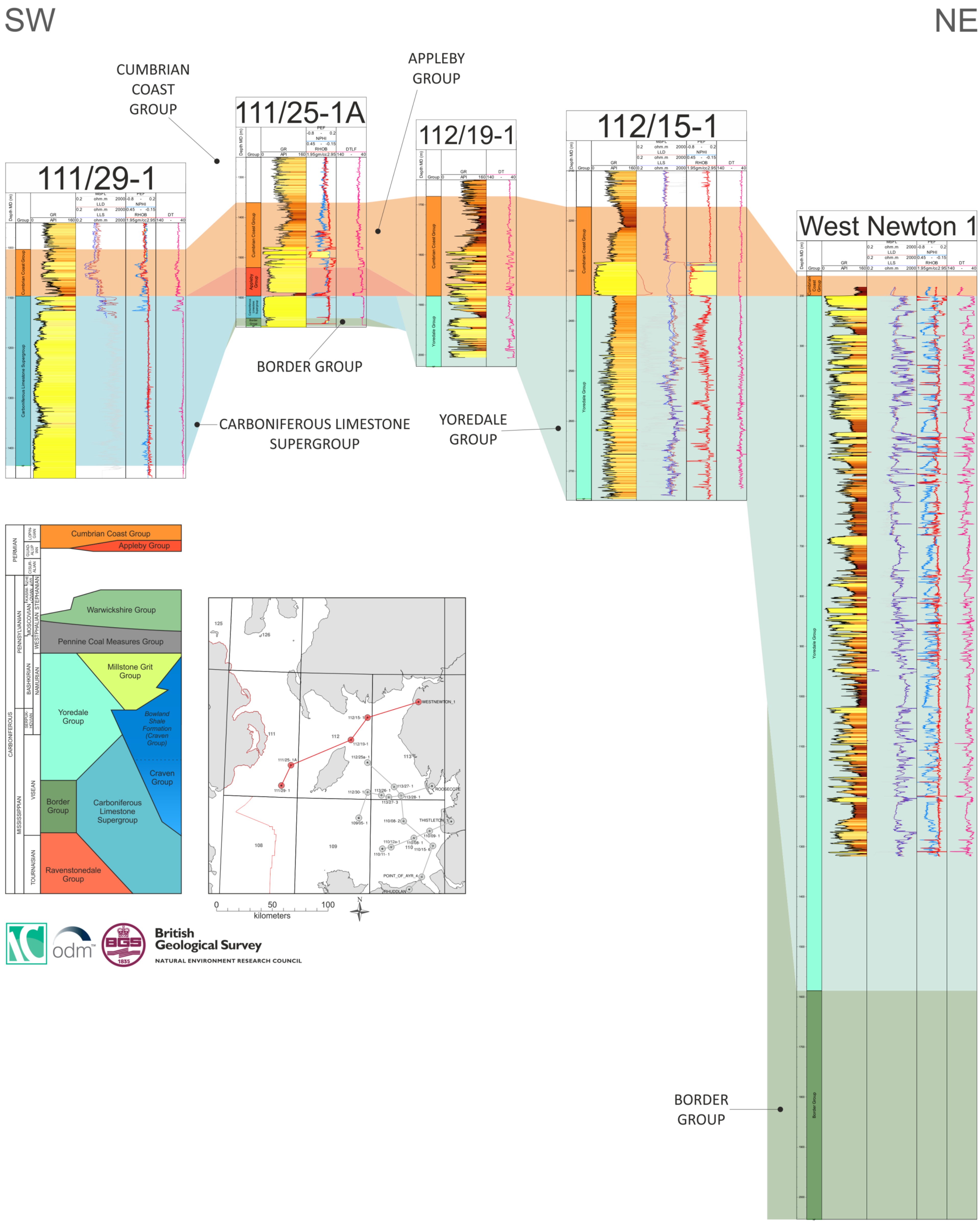

Figure 19 Southwest to northeast correlation of the Carboniferous and Permian strata for the Solway and Manx-Peel Basins.

5 Palaeogeography

Eight time slices are presented from the Mississippian and Pennsylvanian (see Carboniferous timescale in overview report). Six of the time slices represent the addition of interpretations for the Irish Sea to the reconstructions previously generated for the North Sea and onshore area produced by Kearsey et al. (2015). Time slices for the Langsettian and Westphalian D (Asturian) are entirely new palaeogeographical reconstructions for the Irish Sea and onshore regions – no attempt has been made to extend the reconstructions into the North Sea. The maps were constructed using the lithostratigraphy and lithofacies seen in wells and in seismic correlations, arranged in time slices based predominantly on palynology from the well samples. These interpretations have been compared with and in part guided by the palaeogeographical reconstructions of Cope et al. (1992) for the Irish Sea area.

These maps attempt to portray not only where the major lithofacies were deposited during the given time slices, but also incorporate subcrop data to show where these rocks have been removed during late Carboniferous and Early Permian uplift and erosion.

Some general features of the geological evolution of the region are evident from these maps. The Southern Uplands-Down-Longford High forms a persistent upland feature separating the Midland Valley of Scotland and Ireland from the Solway-Northumberland Basin of northern England. Onshore in northern England, sediment accumulation through the Mississippian is controlled by the block and basin structure which became established in Tournaisian times. The markedly thicker succession in the onshore Solway-Northumberland Basin relative to the blocks extends offshore into the Solway and Peel basins, the positions of which broadly coincide with the Iapetus Convergence Zone (Chadwick et al. 2011). During the Visean and Namurian, the Solway Basin and eastern part of the Peel Basin are separated from the main Craven−Dublin Basin by the Manx-Lakeland Ridge and Lake District High, the influence of which are lost during the Westphalian as the region is affected by broad regional thermal subsidence.

5.1 TOURNAISIAN – CHADIAN (CM-PU (EARLY) PALYNOZONE)

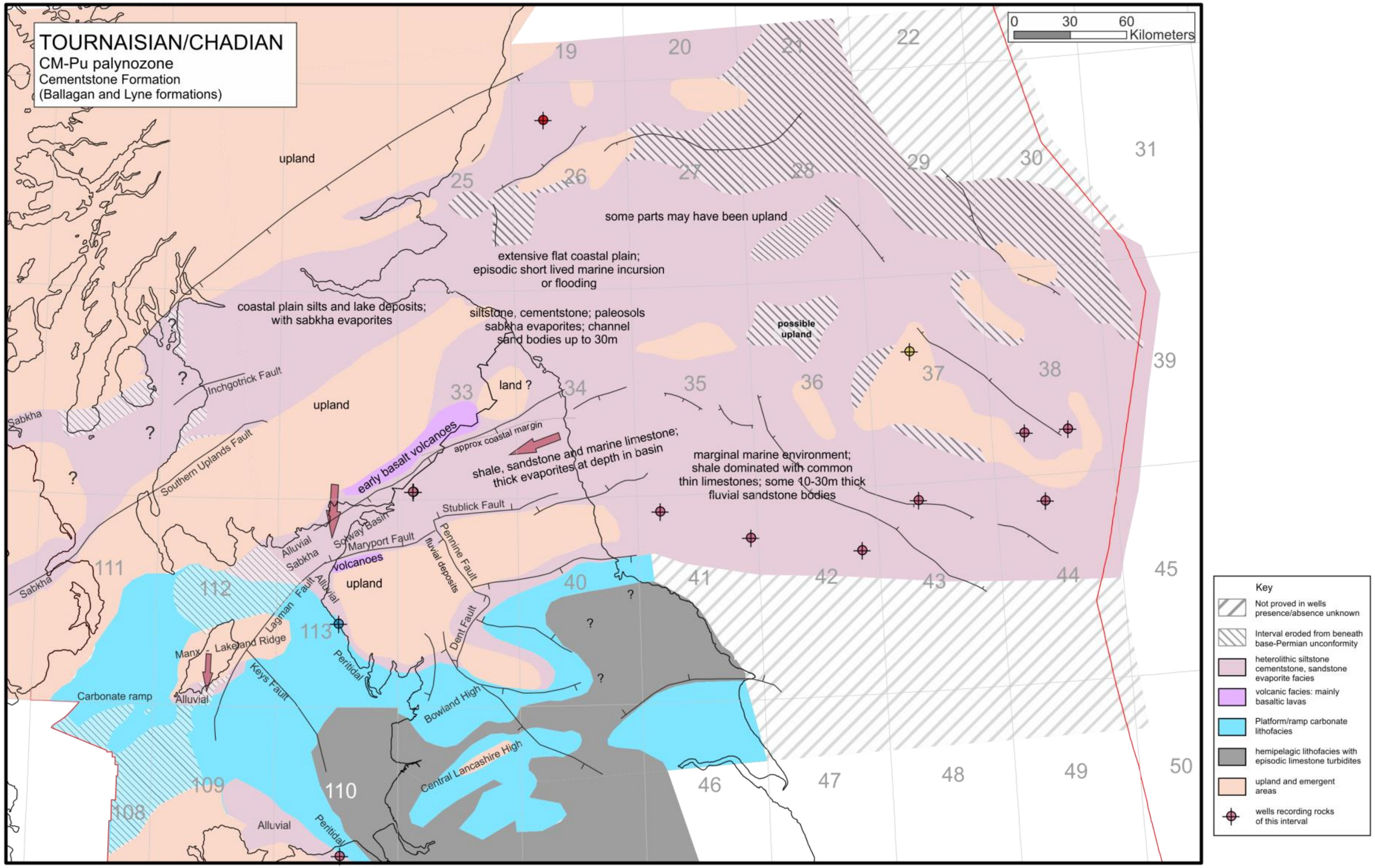

Figure 20 Tournaisian to Chadian palaeogeography (CM- early Pu palynozone)

Tournaisian – Chadian (CM-Pu (early) palynozone)

Offshore: Ravenstonedale Group and Carboniferous Limestone Supergroup (Irish Sea).

Onshore: Ballagan and Lyne formations (Solway−Northumberland Basin); Kinnesswood, Ballagan and Clyde Sandstone formations (Midland Valley of Scotland); Hollywood Group (Northern Ireland)

During this interval, coastal plain to marginal marine conditions were widespread across the northern part of the region, evident as the Ballagan and Lyne formations (Dean et al., 2011; Waters et al. 2011a and c). In the Firth of Clyde area of the western part of the Midland Valley of Scotland, e.g. Arran, Great and Little Cumbrae and Bute and inferred for neighbouring offshore areas, the earliest Tournaisian deposits comprise calcrete-bearing sandstones of the Kinnesswood Formation, deposited within fluvial channels and overbank floodplains. The overlying Ballagan Formation formed in a peritidal environment associated with intermittent emergence. The channel sandbodies present are typically less than 20 m thick, but any substantial lateral continuity has not been proved. The Ballagan Formation is overlain by a fluvial facies of the Clyde Sandstone Formation, ranging from braided stream to floodplain with well-developed overbank deposits. The offshore extensions of these facies into the North Channel are poorly constrained, but are inferred to have been resolved by seismic data (Pharaoh et al., 2016a).

In the Solway-Northumberland Basin of northern England and the Solway Firth coastal areas of Kirkcudbrightshire, Scotland, and also inferred for the offshore Solway Basin, deposition of the Ballagan Formation was dominated by the influx of alluvial fans, and fluvial and fluviodeltaic sediments from the Southern Uplands, intercalated with lacustrine and arid coastal plain deposits (Deegan, 1973; Leeder, 1974). The hypersaline lacustrine and floodplain facies include pseudomorphs after evaporite minerals, some rootlet beds and thin coals is part of the lateral passage to the Lyne Formation in the Solway Basin. The succession was deposited in a rapidly subsiding basin with restricted marine circulation and component limestones are typically peritidal. The sandstones were deposited from lobate deltas that migrated periodically along the basin axis from north-east to south-west (Leeder, 1974). Evaporite deposits (anhydrite and gypsum) are a significant constituent of the sequence in boreholes onshore, representing supra-tidal sabkha deposits, but many of these occurrences are less than 1 m thick. Thicker, probably marine, anhydrite deposits (Easton Anhydrite Member) comprise purer and thicker beds which probably precipitated as gypsum in regionally extensive salinas. These have been reported from the Solway Basin (Ward, 1997) at least 1153 m thick in the Easton Borehole, although seismic data suggests to Ward (1997) that these thick evaporites do not extend westward offshore.

In Northern Ireland, late Tournaisian strata accumulated in a narrow basin, 25 km wide and at least 125 km long, developed on the northern flank of the Southern Uplands-Down-Longford High, which in Belfast Harbour are evident as the Holywood Group (Mitchell, 2004; Mitchell and Somerville, 2011). This group, exposed around Cultra, comprises a basal sandstone-dominated succession deposited in a shallow brackish to non-marine environment with high sediment flux of calcrete-bearing fluvial deposits, sourced from nearby uplands. This passes up into mudstones deposited within sabkha and hypersaline tidal flats similar in appearance to the Lyne Formation. The Roe Valley Group of mainly fluvial conglomerates and overlying lacustrine mudstones and cyanobacterial laminated limestones deposited within a marginal marine environment accumulated within a separate intra-montane basin north of the Sperrin Mountains. Both sabkha deposits present in Northern Ireland are inferred to link with the Firth of Clyde successions, described above, as interpreted on seismic data (Pharaoh et al., 2016a). An evaporitic seaway was proposed by Ward (1997) to have connected the Midland

Valley basins of Scotland and Northern Ireland to those of the Solway Basin, though there is no conclusive evidence of a breach in the Southern Uplands High at this time.

Further alluvial fan deposits (Langness Conglomerate Formation) are found in southern Isle of Man (Dickson et al., 1987; Chadwick et al., 2001; Dean et al., 2011) sourced from the Manx-Lakeland Ridge and west Cumbria (Barclay et al., 1994) probably sourced from the Lake District High. Further accumulations of talus and alluvial deposits during the Chadian (Fernant and Penbedw formations) occurred within fault-controlled palaeovalleys in North Wales (Waters et al., 2009; Davies et al., 2011). In the Rhuddlan Borehole this sandstone facies is at least 82 m thick, although the age has not been established. Onshore, these deposits accumulated with isolated palaeovalleys and there is no proof that these deposits are conjoined and extend across the East Irish Sea.

Carbonate-dominated successions (Martin Limestone Formation) recorded in boreholes along the west Cumbria coast (Sellafield 3) and at crop in Furness, marginal to the Lake District High accumulated in nearshore to peritidal, restricted marine environment, with barrier beach complexes, tidal flats and restricted lagoons (Johnson et al., 2001; Dean et al., 2011). A comparable succession present in North Wales (the Foel Formation) is Late Chadian in age and records peritidal and shallow lagoonal deposition as part of an earliest Visean marine transgression. This is considered to influence large parts of the Irish Sea (northern East Irish Sea, Quad 109, Manx-Peel Basin), though has not been proved in any offshore wells.

Alkali olivine-basalt lavas intercalated with subordinate tuffs (Birrenswark Volcanic Formation) formed during the Mid-Tournaisian main initial phase of extensional faulting associated with development of the Solway-Northumberland Basin, occurring on the southern flanks of the Southern Uplands High (Stephenson et al., 2003; Dean et al., 2011). Additional basaltic and tholeiitic andesite lavas (Cockermouth Volcanic Formation) accumulated on the northern margin of the Lake District High during the late Tournaisian (Stephenson et al., 2003; Dean et al., 2011). No volcanic activity of this age is proved within the Irish Sea, but is possible within the offshore extension of the Solway Basin and has been postulated to form the basal Carboniferous succession, interbedded with shallow-marine carbonates, overlain by Waulsortian mud-mounds in the Peel Basin (Chadwick et al., 2001).

Onshore, the Ballagan Formation mudstones have low TOC values and probably do not have significant source-rock potential (Monaghan, 2014). Similarly, the arid fluvial and hypersaline marginal marine successions found elsewhere during this time interval have low organic contents.

5.2 ARUNDIAN (LATE PU – EARLY TS PALYNOZONES)

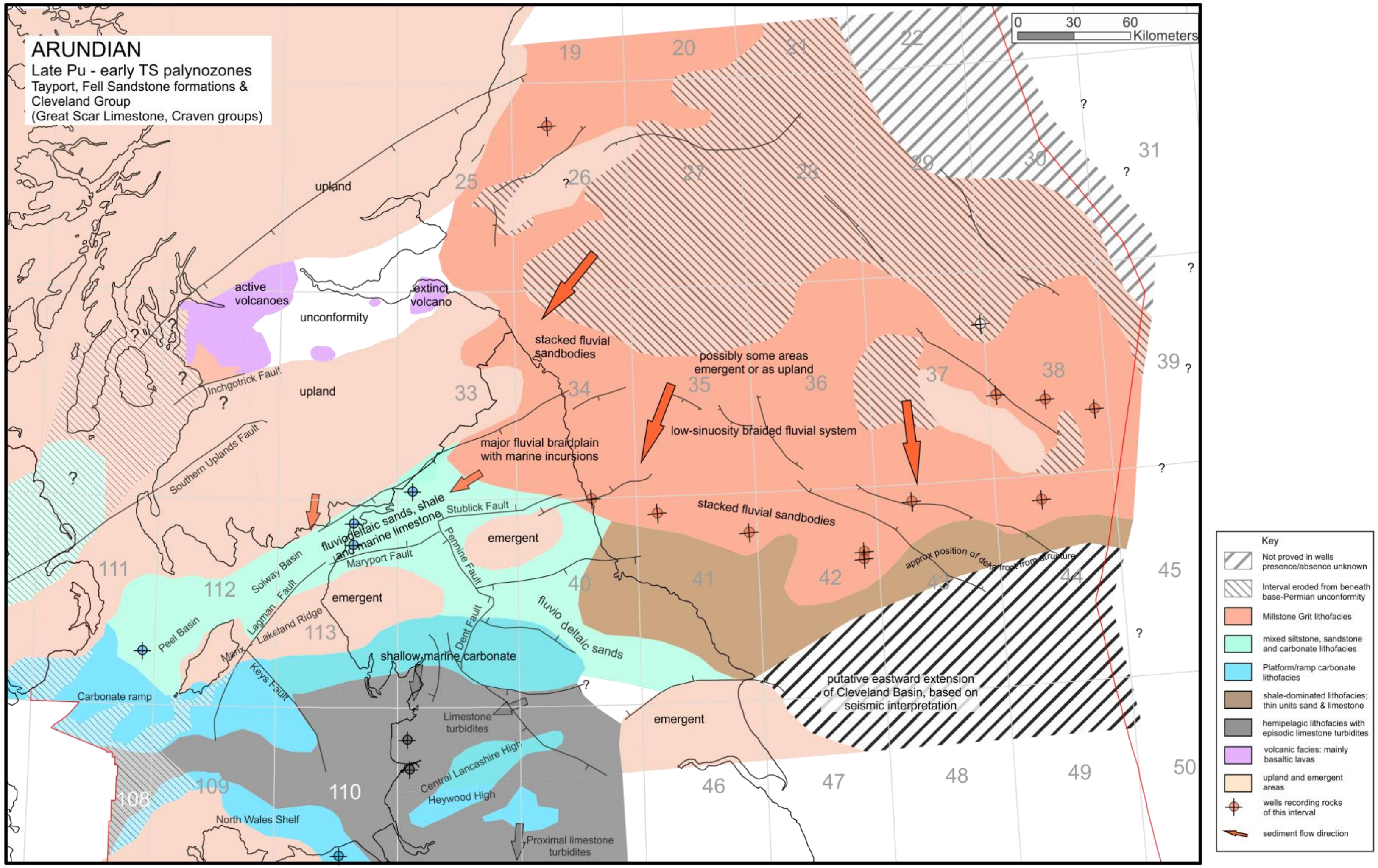

Figure 21 Arundian palaeogeography (Late Pu to early Ts palynozone)

Arundian (Late Pu – early TS palynozones)

Offshore: Carboniferous Limestone Supergroup, Craven Group, Border Group.

Onshore: Fell Sandstone Formation, Great Scar Limestone, Clwyd Limestone Carlingford Limestone groups, Craven Group and Tyrone Group.

Most of the northern part of the region including the Midland Valley of Scotland and Northern Ireland, and probably the intervening North Channel, lack Arundian sediments. In the western part of the Midland Valley, around Glasgow, a thick development of mildly alkaline lava, tuff and volcaniclastic sedimentary rocks (the Clyde Plateau Volcanic Formation) was produced by one major episode of subaerial volcanic activity (Stephenson et al., 2003; Dean et al., 2011).

In the eastern part of the Northumberland Basin a major braided fluvial system (Fell Sandstone Formation) prograded south-westwards to form sandstone sheets that are intercalated with marine siltstones (Turner et al., 1997). This facies passes westward within the Solway Basin into fluviodeltaic sandstones and interbedded shallow marine mudstones and limestones proved in the Easton 1, Westnewton 1 and Silloth 1a boreholes in north Cumbria and are interpreted as extending westward into the Peel Basin, proved in Well 111/25-1A. Arundian conglomerates, deposited in response to either uplift or a major lowstand, have been proposed for the Peel Basin (Chadwick et al., 2001).

The Arundian was a time of marine transgression in which two broad belts of platform carbonates developed within the region. The northern belt is proved onshore in Northern Ireland (Carlingford Limestone Group), deposited on the southern flank of the Southern Uplands-Down-Longford High (Mitchell 2004; Mitchell and Somerville 2011). It also crosses the southern part of the Isle of Man (Derbyhaven Formation, Great Scar Limestone Group), interpreted as a carbonate ramp showing a transgressive succession from lower high energy, shallow marine facies to mid-ramp carbonate facies with storm deposit limestones, and quiet water mudstones and subsequent regression to upper-ramp setting towards the late Arundian (Chadwick et al. 2001; Dean et al. 2011). In Furness, south Cumbria time-equivalent carbonates (Red Hill Limestone and Dalton formations of the Great Scar Limestone Group) show a similar a similar transgressive-regressive-transgressive pattern with an abrupt transition to deeper water limestones recorded in the middle part of the Dalton Formation (Johnson et al., 2001; Dean et al. 2011). The southern carbonate belt forms the North Wales Shelf, proved at crop in the Clwyd area mainly as the Llanarmon Limestone Formation of the Clwyd Limestone Group (Waters et al., 2009; Davies et al., 2011). These limestones formed during a major and sustained Arundian marine transgression and overstepped Lower Palaeozoic rocks forming the Wales-Brabant High (Somerville et al., 1989). The initial distribution of facies suggests a ramp-like setting, with shallower, inner ramp facies to the west. Subsequently, during the late Arundian, these high energy, inner ramp limestones prograded northwards and eastwards to establish a low-gradient carbonate platform (Waters et al., 2009). This carbonate facies is proved in the Rhuddlan Borehole, although the age and component formations have not been established.

Arundian times saw the first establishment of relatively deep marine successions (Craven Group) across the central part of the region, including the Craven Basin, East Irish Sea Basin and extending westward towards the Dublin Basin. The absence of significant coarse-siliciclastics in the East Irish Sea Basin suggests that the Manx-Lakeland Ridge formed a barrier to sediment influx from the Solway-Peel basins, present to the north (Floodpage et al., 2001). The onshore succession (the Hodder Mudstone Formation) is dominated by hemi-pelagic mudstones interbedded with bioclastic limestone turbidites derived from the adjacent carbonate platforms (Riley, 1990). The succession includes local unconformities and relatively steep slopes are evidenced by the common presence of slumps, debris flows and gravity slides (Waters et al. 2009). Onshore the succession is proved in the Thistleton 1 and Becconsall 1Z boreholes. The mudstones of the Craven Group in the Dublin-Craven Basin have moderate TOCs and are a potential shale gas source (Andrews, 2013).

5.3 LATE ASBIAN (NM PALYNOZONE)

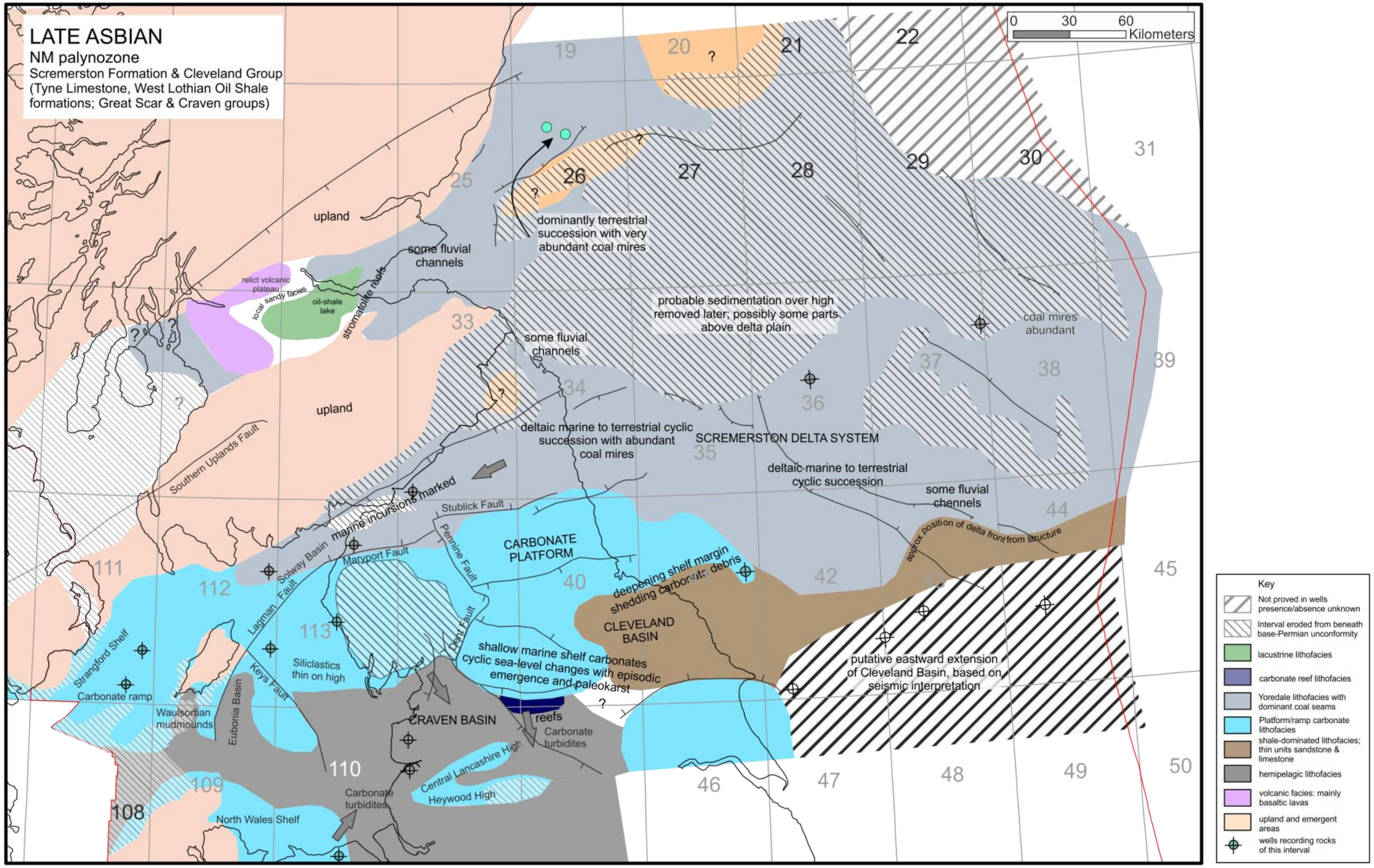

Figure 22 Late Asbian palaeogeography (NM palynozone)

Late Asbian (NM palynozone)

Offshore: Great Scar Limestone, Yoredale and Craven groups.

Onshore: Tyne Limestone Formation (Yoredale Group), Lawmuir Formation/West Lothian Oil-Shale Formation (Strathclyde Group), Balladoole, Eskett Limestone and Urswick Limestone formations (Great Scar Limestone Group). Loggerheads Limestone Formation (Clwyd Limestone Group) and Bowland Shale and Prestatyn Limestone formations (Craven Group).

Late Asbian times saw the first development of the fluvio-deltaic Yoredale facies across the northern part of the region. Glacio-eustatic fluctuations in sea level affected the delta top and delta plain environments by episodic rises in sea-level establishing shallow carbonate platform conditions, followed by clastic sediment infilling accommodation space, resulting in terrestrialisation and development of coal mires, although seam thicknesses are not as great as those seen in Northumberland. On the western side of the Midland Valley of Scotland this facies is evident as the Lawmuir Formation, although the Late Asbian succession is dominated by fluvial facies (Dean et al. 2011). In the Solway Basin the facies is evident as the Tyne Limestone Formation, proved onshore in the Archerbeck Borehole, with the lower part of the Late Asbian succession being dominated by deltaic sandstones (Lumsden and Wilson, 1961), and Westnewton 1 Borehole and offshore in Well 112/15-1. The Yoredale Group has the potential for both source and reservoir rocks, though coals are typically thinly developed.

The previously emergent Lake District, Alston and Askrigg blocks onshore finally became submerged during Asbian time with the establishment of carbonate platforms across much of the northern part of the Irish Sea (Great Scar Limestone Group). Abundant palaeokarstic surfaces in the upper Asbian Eskett Limestone Formation of west Cumbria (proved onshore in the Deep Gill and Sellafield 3 boreholes) and Urswick Limestone Formation of south Cumbria (Great Scar Limestone Group) represent the lateral equivalents of the emergent parts of the Yoredale cycles of the Tyne Limestone Formation Formation. In the southern part of the Isle of Man, the carbonate facies is represented by the Balladoole Formation comprising limestones with mudmounds (bioherms) developed at a shelf margin (Dickson et al. 1987). The offshore continuation of these platform carbonates is seen in the Peel Basin in Wells 111/29-1 and 111/25-1A as high-energy carbonate ramp grainstones and wackestones (Newman, 1999). The former comprises at least 366 m of platform carbonates dated as Holkerian to Asbian, whereas the latter comprises at least 72 m of limestones of uncertain age but considered to be broadly comparable (Newman, 1999). In Northern Ireland the Late Asbian was a time of regional uplift and marine regression (Mitchell, 2004) and no carbonates of this age are recorded.

The southern carbonate belt forms the North Wales Shelf, proved at crop in the Clwyd area mainly as the Loggerheads Limestone Formation of the Clwyd Limestone Group (Waters et al. 2009; Davies et al. 2011). As with the Great Scar Limestone Group of the northern belt, the Loggerheads Limestone shows cyclic shoaling upwards sequences developed in response to transgressive and regressive movements in sea level (Somerville, 1979a). Many regressions culminated in emergence of the platform surface and the formation of calcrete and karstic dissolution features. During these periods of emergence, wind-blown volcanic ash accumulated on the platform surface to form thin bentonitic soils. This southern carbonate facies is proved in the Rhuddlan Borehole, although the age and component formations have not been established.

Late Asbian times saw the persistence of the relatively deep marine successions (Craven Group) across the central part of the region, including the Craven Basin, East Irish Sea Basin and extending westward towards the Dublin Basin. The onshore succession (the earliest Bowland Shale Formation) is dominated by hemi-pelagic mudstones deposited predominantly from suspension in moderately deep water, largely below the storm wave-base. Limestones and sandstones were introduced into the Craven Basin by storms and/or as turbidites derived from the adjacent carbonate platforms and in the Isle of Man in addition to carbonate turbidies there are conglomerates, megaclasts and large olistoliths, representing gravity slides derived from the laterally coeval Balladoole Formation (Dickson et al. 1987). Onshore the succession is proved in the Thistleton 1 and Becconsall 1Z boreholes. The mudstones of the Bowland Shale Formation in the Dublin-Craven Basin are a potential shale gas source (Andrews, 2013).

5.4 BRIGANTIAN (VF PALYNOZONE)

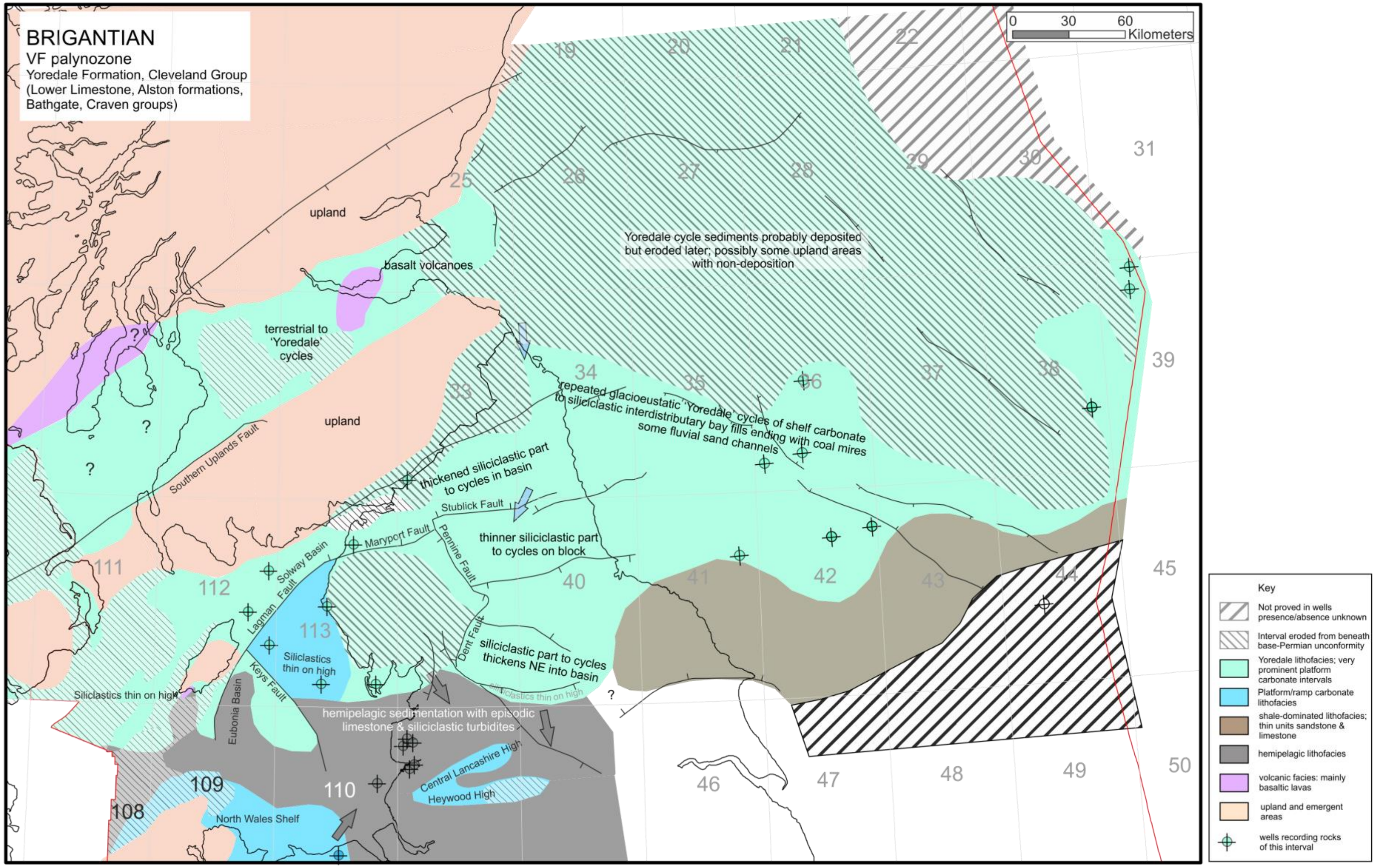

Figure 23 Brigantian palaeogeography (VF palynozone)

Brigantian (VF palynozone)

Offshore: Yoredale, Clackmannan, Clwyd Limestone and Craven groups.

Onshore: Lower Limestone Formation, Alston Formation, Strangford Group, Ballycastle Group, Bowland Shale Formation, Cefn Mawr Limestone Formation and Teilia Formation.

At the onset of Brigantian times, the carbonate platforms of northern England were largely overstepped by the Yoredale facies of fluvio-deltaic clastic sediments with intermittent deposition from shallow carbonate seas. However, platform carbonate deposition persisted in west Cumbria until earliest Pendleian times (Akhurst et al., 1997) and is inferred to extend offshore to wells 112/25a-1 and 113/27-2. Brigantian carbonates in the Lagman and Keys basins are over 110 thick in Well 112/25a-1 and about 150 m thick in 113/27-2 (Chadwick et al. 2001).

During this interval the marine limestones of the Yoredale Group were generally at their thickest development (Alston Formation). with the thickest of these onshore being the Great Limestone, typically about 20 m thick and which occurs at the top of the Alston Formation (Waters et al. 2011c). Onshore, the siliciclastic intervals within the cycles are thickened in the basins, whilst the limestones maintain fairly constant thickness across the area. The Alston Formation is proved in the onshore Archerbeck, Westnewton 1, Deep Gill and Roosecote boreholes and in the northern part of the Isle of Man (Chadwick et al. 2001). The offshore continuation of these cyclic strata is seen in Wells 111/29-1, 111/25-1A and 112/15-1. Well 112/15-1, present in the deepest part of the Solway Basin, comprises about 138 m of Brigantian mudstone with rare thin limestone and sandstone beds. These lack the typical upwards-shallowing cycles of the Yoredale facies and Chadwick et al. (2001) prefers a deep basin with turbidity flows, though such a basin would have to be very locally developed with no connection with the Craven Basin to the south. Chadwick et al. (2001) recorded a carbonate-dominated facies, as 98 m thick in Well 112/19-1, but with component limestones only c. 20 m thick and with significant mudstone partings. This succession is taken to be part of the Yoredale Group.

An equivalent Yoredale facies is evident with the Lower Limestone Formation (of the Midland Valley of Scotland) in which a cyclothemic succession shows increased marine influence and includes both marine and non-marine limestones (Dean et al. 2011). Extensional faulting during the Early Brigantian resulted in the formation of a new fault-bounded sedimentary basin in northeastern Northern Ireland, within which the Ballycastle Group was deposited. A basal alluvial conglomerate is overlain by basaltic volcanism, which in turn is overlain by the Murlough Shale Formation, a 46 m thick oil shale (Mitchell, 2004). Further to the south, the Strangford Group of marine limestones and shales locally accumulated in Strangford Lough (Mitchell, 2004). This may have provided a connection through the Southern Uplands between the Midland Valley of Scotland to Ballycastle depositional basin to the north and the Solway-Peel Basin to the south.

Brigantian times saw the persistence of the relatively deep marine successions (Craven Group) across the central part of the region, including the Craven Basin, East Irish Sea Basin and extending westward towards the Dublin Basin. The onshore succession (the Bowland Shale Formation) is dominated by hemi-pelagic mudstones deposited predominantly from suspension in moderately deep water, largely below the storm wave-base. Limestones and sandstones were introduced into the Craven Basin by storms and/or as turbidites derived from the adjacent carbonate platforms to the north. The reef marginal succession that was present on the southern flank of the Askrigg Block was finally submerged and overstepped by the Bowland Shales. In the southern part of the Isle of Man, the black hemipelagic mudstones, carbonate turbidites and olistoliths of the Bowland Shale Formation continue to accumulate, with the local development of the Scarlett Volcanic Member comprising waterlain tuffs, and submarine volcaniclastic debris flows and gravity slides (Dickson et al. 1987; Chadwick et al. 2001; Dean et al. 2011). A carbonate turbiditic and hemipelagic marine mudstone facies (Teilia Formation) onlapped the northern margin (including knoll reefs) of the North Wales Shelf during the Brigantian (Waters et al. 2009), with turbidites sourced from the platform to the south. Onshore the Brigantian hemi-pelagic succession is proved in the Preese Hall 1, Grange Hill 1Z, Thistleton 1, Becconsall 1Z and Hesketh 1 boreholes and offshore in Well 110/15-6.

The last remnants of the thick Visean platform carbonates continued to accumulate on the Central Lancashire and Heywood highs and on the North Wales Shelf. The latter comprises the Cefn Mawr Limestone Formation, in which cyclic sequences record shoaling upwards units developed in response to transgressive and regressive movements in sea level. Many regressions culminated in emergence of the platform surface and formation of calcrete and karstic dissolution features (Somerville, 1979b; Waters et al., 2009). This southern carbonate facies is proved in the Rhuddlan Borehole, although the age and component formations have not been established.

The Yoredale Group has the potential for both source and reservoir rocks, though coals are typically thinly developed. However, the limestones are characteristically dark and bituminous. In general, both the limestone and sandstone beds, which locally occupy incised fluvial channel systems, are typically sub-seismic resolution, except with the highest quality data. Deep marine shales of the Bowland Shale Formation are a potential shale gas prospect (Andrews, 2013).

5.5 PENDLEIAN (NC PARS PALYNOZONE)

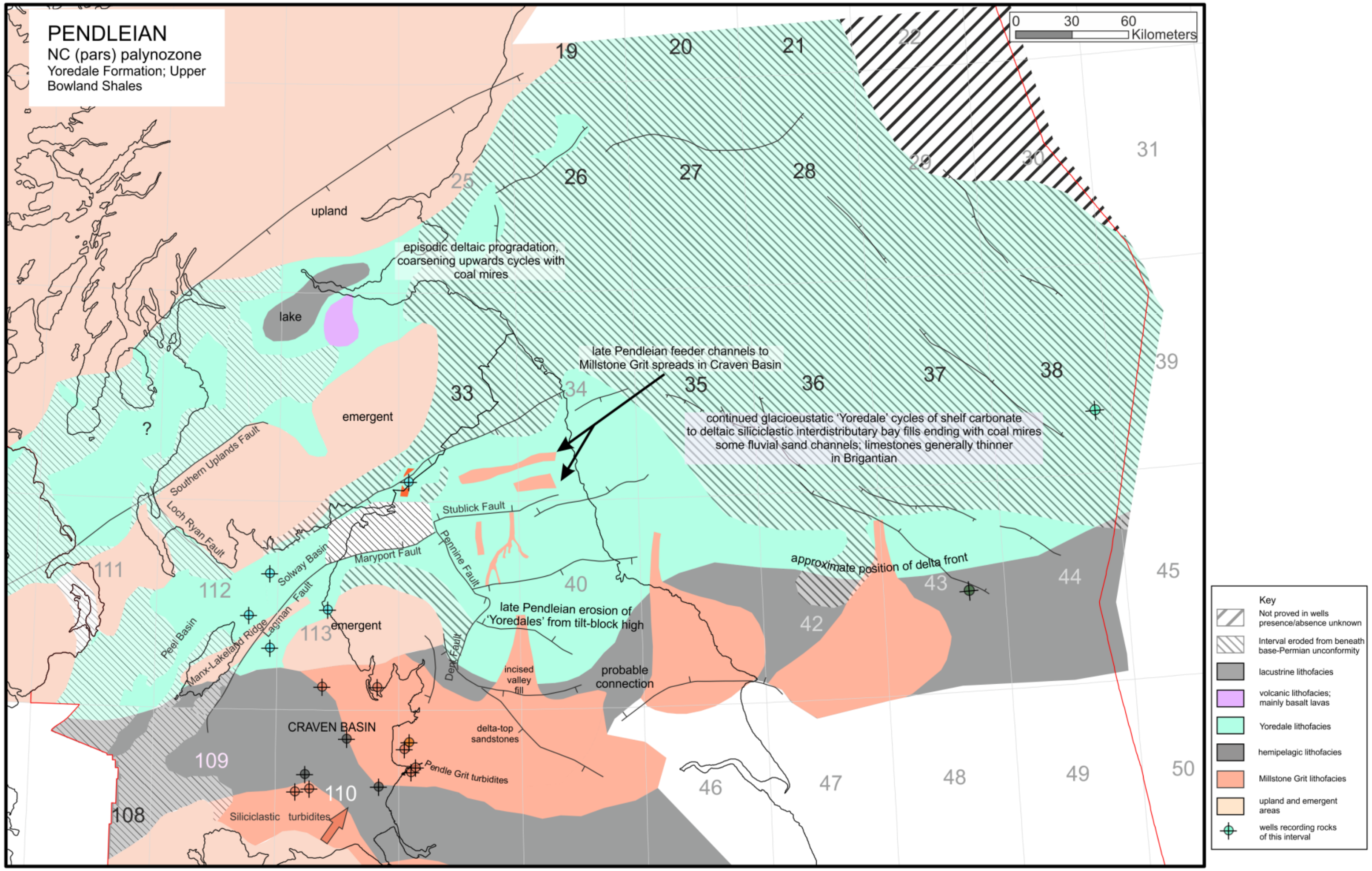

Figure 24 Pendleian palaeogeography (NC palynozone).

Pendleian (NC pars palynozone)

Offshore: Yoredale, Clackmannan, Craven (Upper Bowland Shales) and Millstone Grit groups.

Onshore: Limestone Coal, Upper Limestone, Alston and Stainmore formations, Millstone Grit Group (Pendleton and Cefn-y-fedw Sandstone formations), Craven Group (Bowland Shale Formation) and Ballycastle Group.

The Yoredale fluvio-deltaic clastic to marine carbonate facies continued through Pendleian. In the Midland Valley of Scotland, the early Pendleian succession is dominated by upward-coarsening fluvio-deltaic cycles, usually capped by seatearth and coal (Limestone Coal Formation), representing periodic delta progradation (Dean et al. 2011). The late Pendleian succession differs in an increased abundance of marine limestones and mudstones within the cycles, particularly to the west, which is used to infer increasingly marine conditions in that direction (Francis, 1991). The westward continuation of this succession is seen in Northern Ireland as the uppermost component of the Ballycastle Group, the Ballyvoy Sandstone Formation, which comprises a cyclic succession of Yoredale facies which includes coal seams of variable quality and represents periodic fluviodeltaic, coal mire and marine transgressions (Mitchell, 2004).

In northern England the thickest of the marine limestones of the Yoredale Group, the Great Limestone Member, which is about 20 m thick (Waters et al. 2011c), was deposited at the onset of the Pendleian (and the top of the Alston Formation). Above the Great Limestone, the limestones are thinner and more difficult to recognise in the wells. Fluvial, fine to medium-grained sandstones become progressively more significant within the succession. Onshore, incised channels filled with coarse-grained sandstone are inferred to feed the sandstone deltas seen to the south in the Craven Basin (Waters et al. 2014). Onshore the Pendleian Yoredale facies is proved in the Archerbeck and Deep Gill boreholes, in the northern part of the Isle of Man (Chadwick et al. 2001), and offshore in Wells 112/15-1, 112/25a-1. Chadwick et al. (2001) recorded siliciclastic-dominated Yoredale facies as 100 m thick in Well 112/19-1, but with an absence of coals within the cycles thought to be due to a delta-front setting of this well (Newman, 1999). A high gamma mudstone is overlain by an upward- coarsening succession with a few limestones, the succession being organically lean, with TOC up to 0.82% (Newman, 1999). Well 112/15-1 from the deepest part of the Solway Basin comprises 148 m of Pendleian mudstones, sandstones, coals and carbonates, which Chadwick et al. (2001) attributes to deeper water environments, though the presence of characteristic Yoredale facies would suggest that this is a local development lacking significant deltaic influx.

Pendleian times saw the persistence of the relatively deep marine hemi-pelagic successions (Upper Bowland Shales) across the central part of the region, including the Craven Basin, East Irish Sea Basin and extending westward towards the Dublin Basin. In North Wales a basinal succession of cherts and cherty mudstones (the Pentre Chert Formation) underlies the Bowland Shales. Chert-rich successions, representing extensive secondary silicification, are a feature of diverse environments, also developing at the same time on the Askrigg Block, within Yoredale facies. Onshore the succession can show increasing upwards presence of thin turbiditic sandstones. Onshore this facies is evident in the Roosecote, Preese Hall 1, Grange Hill 1Z, Thistleton 1, Becconsall 1Z and Hesketh 1 boreholes and offshore in Wells 110/07b-6, 110/15-6 and 113/27-2. Seismic and drilling information show that this facies, of general Namurian age, is present in Block 110/13 and to be the source of the oil present in the Douglas Field (Armstrong et al. 1997; Yaliz and McKim, 2003). Well 110/13-1 shows TOC values for this facies between 1.0 and 1.6% and V_R of 0.55 to 1.17% (Yaliz and McKim, 2003).

The late Pendleian saw the first major influx of thick fluvial and deltaic sandstones into the Craven Basin, both from the north (Pendleton Formation) and from the south (Cefn-y-fedw Formation). The northern basin fill are characterized by a thick pro-deltaic ramp turbidites (Pendle Grit Member), overlain by a siltstone-dominated slope succession (Surgill Shale), in turn overlain by a fluvio-deltaic, delta-top sandstone (Warley Wise Grit) (Waters et al. 2011d). The arenaceous components are dominantly quartz-feldspathic and of northern (Scandinavian) provenance. Onshore this facies is evident the Roosecote, Preese Hall 1, Grange Hill 1Z, Thistleton 1, Becconsall 1Z and Hesketh 1 boreholes and offshore in Wells 110/03-2, 110/15-6 and 113/27-2. The southern basin fill differs in being quartzitic and derived from the Wales-Brabant High present to the south. This facies is seen in the offshore wells 110/11-1, 110/12b-2.

The high gamma values for the Upper Bowland Shales offshore suggest that these rocks have the potential as source rocks. The Yoredale Group has the potential for both source and reservoir rocks, though coals are typically thinly developed, except within the age-equivalents of the Midland Valley of Scotland.

5.6 KINDERSCOUTIAN (EARLY KV PALYNOZONE)

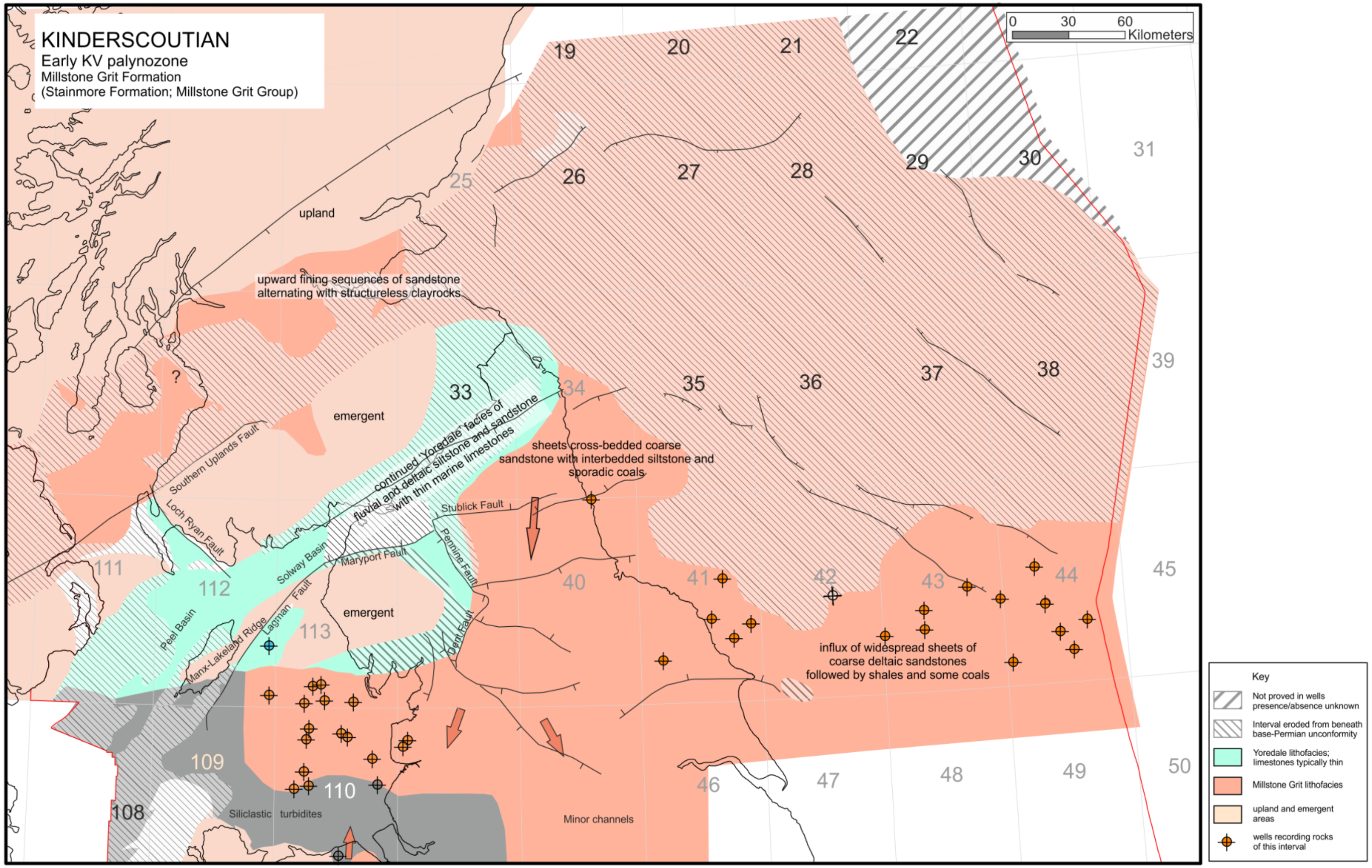

Figure 25 Kinderscoutian palaeogeography (Early KV palynozone)

Kinderscoutian (early KV palynozone)

Offshore: Yoredale, Clackmannan, Craven (Upper Bowland Shales) and Millstone Grit groups.

Onshore: Passage, Stainmore, Millstone Grit Group (Hebden formations and Cefn-y-fedw Sandstone formations), Craven Group (Bowland Shale Formation).

Yoredale facies rocks continued to dominate in the Solway-Northumberland Basin (Waters et al. 2014), the Peel Basin and marginal to the Lake District High and Manx-Lakeland Ridge. The succession was proved in the area southeast of the Lagman Fault in Well 112/25a-1. No strata of Kinderscoutian age have been recorded from Northern Ireland, with renewed uplift creating a mid-Carboniferous hiatus (Mitchell 2004; Mitchell and Somerville 2011).

With renewed uplift in the Caledonide source region to the north-east, sheets of coarse fluvial sandstone spread across much of the onshore part of the Midland Valley of Scotland (Passage Formation) and northern England (Hebden Formation), with the exception of the Solway Basin. In Scotland the succession is dominated by upward-fining sandstones alternating with structureless clayrocks (including some high-alumina seatclay, fireclay and bauxitic clay sourced from weathering of basaltic volcanic rocks). In the western Midland Valley of Scotland thickness variations are marked, controlled by movements on faults of NE−SW orientation and sediment accumulation between basaltic lavas (Read, 1988). In areas of the southern part of the region, where this Millstone Grit Group represented the initial northern basin fill. e.g. onshore within the Edale Basin, the succession is characterized by a thick pro-deltaic ramp turbidites (Mam Tor Sandstone), overlain by a siltstone-dominated slope succession (Grindslow Shales), in turn overlain by a fluvio-deltaic, delta-top sandstone (Kinderscout Grit) (Waters et al. 20011d). Onshore this facies is evident in the Preese Hall 1 and Grange Hill 1Z boreholes and offshore in Wells 110/02b-9, 110/02b-10, 110/03-2, 110/03b-4, 110/07-2, 110/09-1, 110/11-1, 110/12b-2, 110/15-6, 113/27-1, 113/27-2, 113/27-3, 113/28-1 and 113/29-2. In onshore North Wales, a subordinate fluvio-deltaic system continued to be fed from the south (Cefn-y-fedw Sandstone), though appears not to extend far offshore at this time.

By Kinderscoutian times the relatively deep marine hemi-pelagic successions (Upper Bowland Shales) had become mainly restricted in extent to the southern parts of the onshore Craven Basin and East Irish Sea Basin, but is inferred to be extensively developed south of the Isle of Man and westward towards the Dublin Basin. Well 112/30-1 proves a 162 m thick, mudstone-dominated succession, but with a 13 m thick sandstone present within the middle part of the succession (Jackson et al., 1995), possibly representing the first distal influence of the Kinderscoutian river system into this part of the Ogham Platform.

The thick sandstones of the Hebden Formation are potentially reservoir rocks in the East Irish Sea Basin of Quadrants 110 and 113, particularly to the south of the extent of the Pendleton Formation, where the Hebden Formation directly overlies the Bowland Shale Formation source rocks.

5.7 LANGSETTIAN (SS-RA PALYNOZONES)

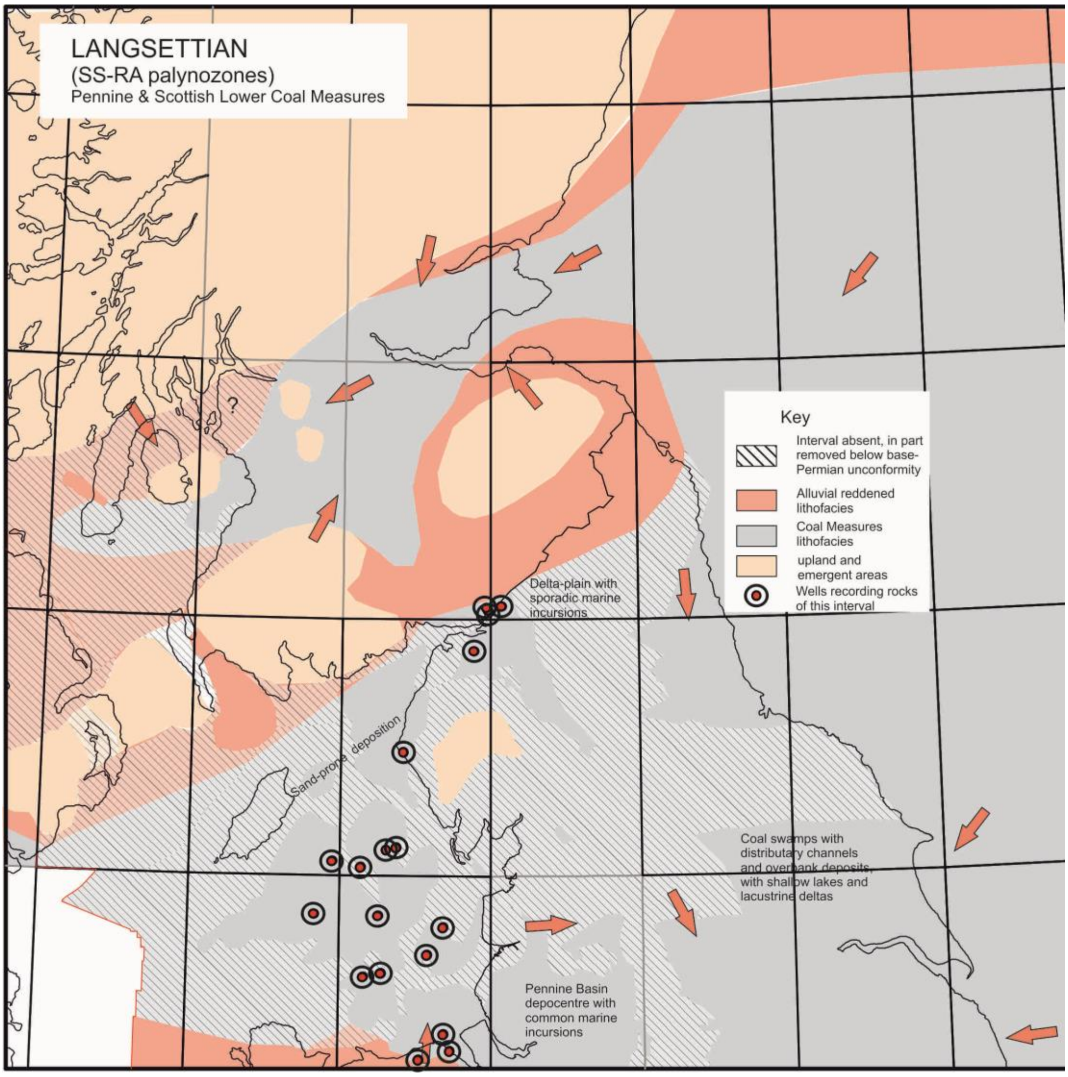

Figure 26 Langsettian palaeogeography (SS-RA palynozones).

Langsettian (SS-RA palynozones)

Offshore: Scottish and Pennine Coal Measures groups.

Onshore: Scottish and Pennine Coal Measures groups.

By Langsettian times the basinal areas where infilled and generally low topographical gradients existed across the region. The Southern Uplands still separated the Midland Valley of Scotland and Pennine Basin, but was locally breached within the NW-trending grabens of Stranraer, Thornhill and Sanquhar (Waters et al. 2011a). The depositional environments typical of the Coal Measures facies include prograding lacustrine deltas (upward-coarsening arenaceous sequences), floodplain (planty or rooted siltstone and mudstone), shallow freshwater to brackish lakes (mudstones with non-marine faunas and crevasse splay sandstones), river and delta distributary channels (sandstones up to 20 m thick and 20 km wide) and wetland forest and soils (coal and seatrock). Marine bands, which resulted from marine transgressions, occur mainly in the early Langsettian, but are either absent or rarely present in the periphery of the basins, e.g. Mull of Kintyre (Waters et al. 2011a), Canonbie Coalfield (Waters et al. 2011c) and North Wales (Davies et al. 2011). Within the basin margins, red-beds successions may interdigitate with the Coal Measures, representing areas of improved drainage adjacent to palaeo-highs. Localised uplift resulted in development of unconformities at the base of the Westphalian successions in Canonbie and north Ayrshire, the latter being associated with volcanic activity.

The Midland Valley of Scotland saw deposition of the Coal Measures facies coincident with active dextral strike-slip deformation accompanied by magmatism (Read 1988). Within Arran and Machrihanish, in the Firth of Clyde, the Langsettian strata are about 65−70 m thick (Dean et al. 2011; Waters et al. 2011a), with the partially reddened succession in Arran interpreted as proximal alluvial plain deposits locally sourced from the north or northwest (Kirk, 1989). About 30 m of grey, red and mottled yellow-brown sandstones interbedded with purple-grey shales are present within the Stranraer Basin. Langsettian strata are largely absent from Northern Ireland. The Ballavaarkish Borehole on northern Isle of Man records a minimum of 18 m of Langsettian Coal Measures, but lacking any coal (Chadwick et al. 2001). An absence of Coal Measures facies over the offshore Solway and Peel basins is considered to be a consequence of Late Carboniferous inversion of the basin and subsequent removal through erosion (Newman, 1999)

Within the Pennine Basin depocentre in south Lancashire, the Langsettian succession is 830 m thick (Waters et al. 2011d). The succession is proved onshore in Becklees, Becklees 2, Englishtown 1, Bruntons Hill Farm, Deep Gill, Liverpool Bay, Rhuddlan and Mostyn Quay 1 boreholes and offshore in Wells 109/05-1, 110/02b-10, 110/09a-2, 110/11-1, 110/12a-1, 112/30-1, 113/27-1, 113/27-2 and 113/26-1. Up to 425 m of probable Langsettian reddened Coal Measures strata are recorded in Well 112/30-1 on the Ogham Platform (Chadwick et al. 2001) and 120 m was recorded by Jackson et al. (1997). Immediately offshore of North Wales, deposition of Coal Measures facies gradually transgressed southwards onto the Central Irish Sea Basin (Floodpage et al., 2001)

The thickest and least sulphurous coal seams are typically present within the late Langsettian succession.

5.8 ASTURIAN OR WESTPHALIAN D (EARLY OT PALYNOZONE)

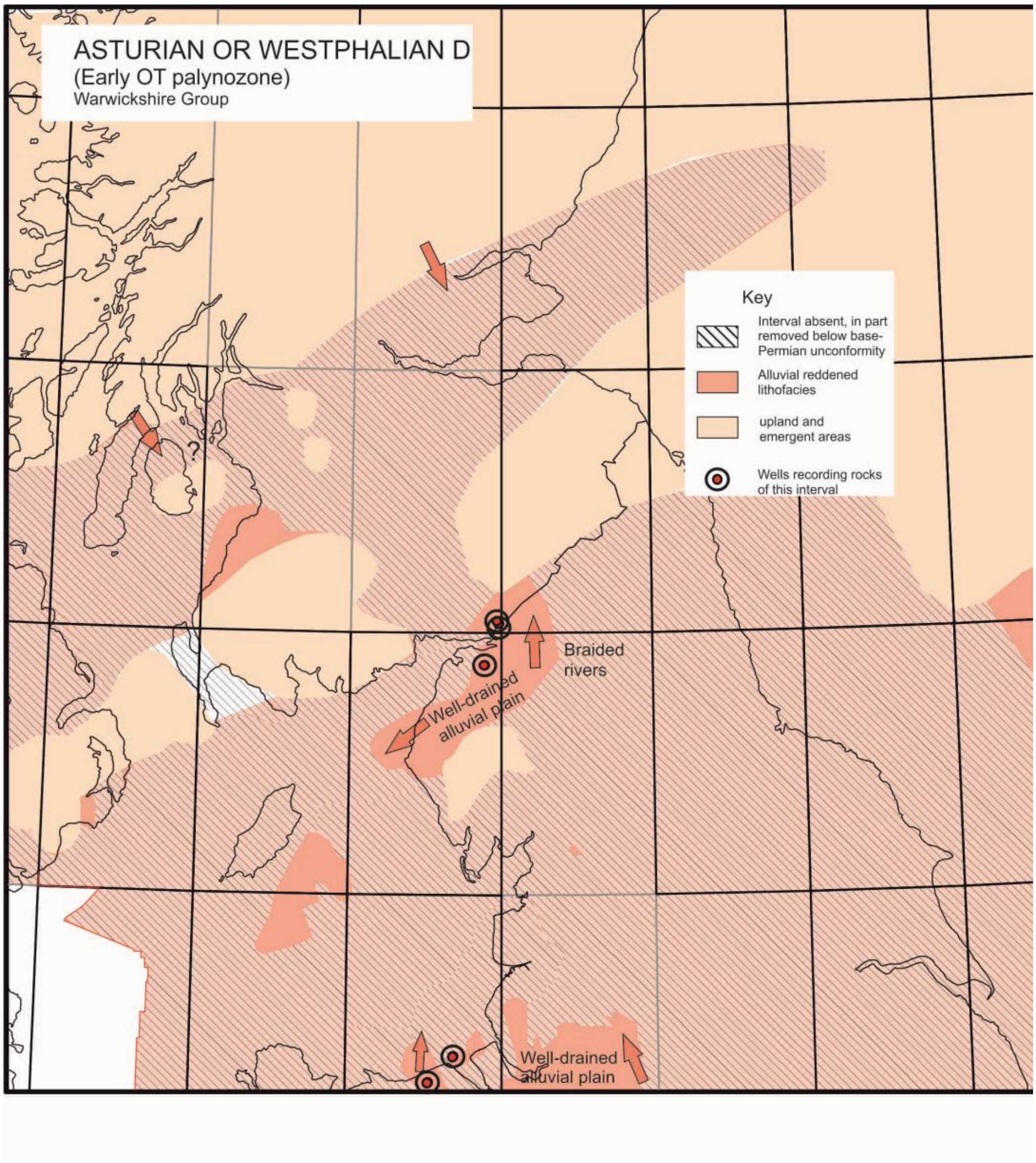

Figure 27 Asturian palaeogeography (Early OT palynozones)

Asturian or Westphalian D (Early OT palynozone)

Offshore: Warwickshire Group.

Onshore: Warwickshire Group, Scottish Upper Coal Measures Formation.

By late Westphalian times, early stages in the Variscan inversion of both the Midland Valley of Scotland and Pennine Basin (Waters et al. 1994) resulted in localized development of condensed successions and unconformities associated with growth anticlines. The climax of this inversion has resulted in most of the Asturian succession being removed beneath the End Carboniferous (Variscan) Unconformity across most of the Midland Valley of Scotland, the eastern parts of England and the northern and western parts of the Irish Sea.

Within the Midland Valley of Scotland Coal Measures facies continue into the Asturian, but are typically secondarily reddened beneath the End Carboniferous unconformity and coal seams are thin and may be locally replaced by hematitic carbonate (Dean et al. 2011). Only the succession in Ayrshire extends up into the Asturian.

Within the Pennine Basin strata comprising well-drained primary red-bed alluvial floodplain and fluvial channel facies predominate. Coal-poor grey measures, representing the northern extension of the Pennant Measures sourced from France, are present in the southern part of the Pennine Basin, including North Wales, proved in the Rhuddlan, Point of Ayr 4 and Liverpool Bay boreholes and described by Williams and Eaton (1993). However, sediments containing sandstones of similar provenance have been found in the Canonbie Coalfield (Jones et al. 2011) where a thick Asturian succession is preserved (Chadwick et al. 1995) and proved in the Fisher Gill, Becklees and Englishtown 1 boreholes. In west Cumbria, a major braided river system that flowed from the north-east (the Whitehaven Sandstone Formation) is present (Akhurst et al., 1997) and is recorded in the Deep Gill Borehole. An untested Asturian succession is proposed within the Quadrant 109 Syncline (Jackson and Johnson, 1996) and is mapped seismically in this study (Pharaoh et al.2016a).

The sandstones of the formation are potentially reservoir rocks in the western part of Quadrant 113, where the Whitehaven Sandstone extends offshore.

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Appendix 1

Biostratigraphic correlations used in this project.

These are all taken from C.N.WATERS, I. D. SOMERVILLE, M. H. STEPHENSON, C. J. CLEAL AND S. L. LONG, ‘Chapter 3 Biostratigraphy, *in "A revised correlation of Carboniferous rocks in the British Isles."* Geological Society of London, 2011,

Marine band and Ammonid Zones

REGIONAL STAGES	REGIONAL SUBSTAGES	ZONES Index	ZONES Ammonoid	WESTERN EUROPEAN MARINE BANDS Index	WESTERN EUROPEAN MARINE BANDS Ammonoid
WESTPHALIAN	Langsettian (pars)	G2	*Gastrioceras listeri*		
			Gastrioceras subcrenatum		
NAMURIAN	Yeadonian	G1b	*Cancelloceras cumbriense*	G1b1	*Ca. cumbriense*
		G1a	*Cancelloceras cancellatum*	G1a1	*Ca. cancellatum*
	Marsdenian	R2c	*Bilinguites superbilinguis*	R2c2	*Verneulites sigma*
				R2c1	*B. superbilinguis*
		R2b	*Bilinguites bilinguis*	R2b5	*B. metabilinguis*
				R2b4	*B. eometabilinguis*
				R2b3	*B. bilinguis*
				R2b2	*B. bilinguis*
				R2b1	*B. bilinguis*
		R2a	*Bilinguites gracilis*	R2a1	*B. gracilis*
	Kinderscoutian	R1c	*Reticuloceras reticulatum*	R1c4	*R. coreticulatum*
				R1c3	*R. reticulatum*
				R1c2	*R. reticulatum*
				R1c1	*R. reticulatum*
		R1b	*Reticuloceras eoreticulatum*	R1b3	*R. stubblefieldi*
				R1b2	*R. nodosum*
				R1b1	*R. eoreticulatum*
		R1a	*Hodsonites magistrorum*	R1a5	*R. dubium*
				R1a4	*R. todmordenense*
				R1a3	*R. subreticulatum*
				R1a2	*R. circumplicatile*
				R1a1	*Ho. magistrorum*
	Alportian	H2c	*Vallites eostriolatus*	H2c2	*Homoceratoides prereticulatus*
				H2c1	*V. eostriolatus*
		H2b	*Homoceras undulatum*	H2b1	*H. undulatum*
		H2a	*Hudsonoceras proteum*	H2a1	*Hd. proteum*
	Chokierian	H1b	*Homoceras beyrichianum*	H1b2	*Isohomoceras. sp. nov.*
				H1b1	*H. beyrichianum*
		H1a	*Isohomoceras subglobosum*	H1a3	*I. subglobosum*
				H1a2	*I. subglobosum*
				H1a1	*I. subglobosum*
	Arnsbergian	E2c	*Nuculoceras stellarum*	E2c4	*N. nuculum*
				E2c3	*N. nuculum*
				E2c2	*N. nuculum*
				E2c1	*N. stellarum*
		E2b	*Cravenoceratoides edalensis*	E2b3	*Ct. nititoides*
				E2b2	*Ct. nitidus*
				E2b1	*Ct. edalensis*
		E2a	*Cravenoceras cowlingense*	E2a3	*Eumorphoceras yatesae*
				E2a2a	*C. gressinghamense*
				E2a2	*Eumorphoceras ferrimontanum*
				E2a1	*C. cowlingense*
	Pendleian	E1c	*Cravenoceras malhamense*	E1c1	*C. malhamense*
		E1b	*Cravenoceras brandoni*	E1b2	*Tumulites pseudobilinguis*
				E1b1	*C. brandoni*
		E1a	*Cravenoceras leion*	E1a1	*C. leion*
VISEAN	Brigantian	P2c	*Lyrogoniatites georgiensis*		
		P2b	*Neoglyphioceras subcirculare*		
		P2a	*Lusitanoceras granosus*		
		P1d	*Paraglyphioceras koboldi*		
		P1c	*Paraglyphioceras elegans*		
		P1b	*Arnsbergites falcatus*		
	Asbian	P1a	*Goniatites crenistria*		
		B2b	*Goniatites globostriatus*		
		B2a	*Goniatites hudsoni*		
		B1			
	Holkerian	BB	*Bollandites-Bollandoceras*		
	Arundian				
	Chadian	FA	*Fascipericyclus-Ammonellipsites*		
TOURNAISIAN	Courceyan		*Pericyclus*		
			Gattendorfia subinvoluta		

Miospore zonation

STAGES	SUBSTAGES	FORMER INDEX	INDEX	ZONES	SUBZONE
AUT-UNIAN	Lower Autunian		VC	*Vittatina costabilis*	
STEPHANIAN	Stephanian C, Stephanian B	XII	NBM	*Potonieisporites novicus-bhardwajii-Cheiledonites major*	
STEPHANIAN	Stephanian B, Barruelian	XII	ST	*Angulisporites splendidus-Latensina trileta*	
STEPHANIAN / WESTPHALIAN	Cantabrian, Asturian	XII, XI	OT	*Thymospora obscura-T. thiessenii*	
WESTPHALIAN	Bolsovian	X	SL	*Torispora securis- T. laevigata*	
WESTPHALIAN	Bolsovian, Duckmantian	IX, VIII, VII	NJ	*Microreticulatisporites nobilis-Florinites junior*	
WESTPHALIAN	Langsettian	VI	RA	*Radiizonates aligerens*	
WESTPHALIAN	Langsettian	SS	SS	*Triquitrites sinani-Cirratriradites saturni*	
NAMURIAN	Yeadonian, Marsdenian	FR	FR	*Raistrickia fulva-Reticulatisporites reticulatus*	
NAMURIAN	Marsdenian, Kinderscoutian	KV	KV	*Crassispora kosankei-Grumosisporites varioreticulatus*	
NAMURIAN	Alportian, Chokierian	SO	SO / SR	*Lycospora subtriquetra-Kraeuselisporites ornatus*	*L. subtriquetra-Cirratriradites rarus*
NAMURIAN	Arnsbergian	SO	SO / SV	*Lycospora subtriquetra-Kraeuselisporites ornatus*	*L. subtriquetra-Apiculatisporis variocorneus*
NAMURIAN	Arnsbergian	TK	TK	*Mooreisporites trigallerus-Rotaspora knoxi*	
NAMURIAN	Pendleian	NC	CN / Vm	*Reticulatisporites carnosus-Bellispores nitidus*	*Verrucosisporites morulatus*
VISEAN	Brigantian	NC	CN / Cc	*Reticulatisporites carnosus-Bellispores nitidus*	*Cingulizonates* cf. *capistratus*
VISEAN	Brigantian	VF	VF	*Tripartites vetustus-Rotaspora fracta*	
VISEAN	Asbian	NM	NM / ME	*Raistrickia nigra-Triquitrites marginatus*	*Murospora margodentata-Rotaspora ergonulii*
VISEAN	Asbian	NM	NM / DP	*Raistrickia nigra-Triquitrites marginatus*	*Tripartites distinctus-Murospora parthenopia*
VISEAN	Asbian	TC	TC	*Perotrilites tessellatus-Schulzospora campyloptera*	
VISEAN	Asbian, Holkerian, Arundian	Pu	TS	*Knoxisporites triradiatus-Knoxisporites stephanephorus*	
VISEAN	Arundian, Chadian	Pu	Pu	*Lycospora pusilla*	
TOURNAISIAN	Courceyan	CM	CM	*Schopfites claviger-Auroraspora macra*	
TOURNAISIAN	Courceyan	CM	PC	*Spelaeotriletes pretiosus-Raistrickia clavata*	
TOURNAISIAN	Courceyan	VI	BP	*Spelaeotriletes balteatus-Rugospora polyptycha*	
TOURNAISIAN	Courceyan	VI	HD	*Kraeuselisporites hibernicus-Umbonatisporites distinctus*	
TOURNAISIAN	Courceyan	VI	VI	*Vallatisporites vallatus-Retusotriletes incohatus*	