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Devonian and Carboniferous stratigraphical correlation and interpretation in the Central North Sea, Quadrants 25 – 44

Energy and Marine Geoscience Programme

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Devonian and Carboniferous stratigraphical correlation and interpretation in the Central North Sea, Quadrants 25 – 44

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Keywords

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Front cover

View of foreshore at Spittal, Berwick-upon-Tweed. Rocks in the foreshore belong to the Scremerston Coal Member, equivalent to the Scremerston Formation offshore. P662948 ©BGS NERC

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Foreword

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

Acknowledgements

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

P. Osterloff (Shell), T. Parsons (Centrica) and C. Mathieu (OGA) are thanked for technical review of this report and associated digital data.

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Summary

This report details the stratigraphy and palaeogeography of Devonian and Carboniferous rocks of the UK Central North Sea for the 21CXRM Palaeozoic project. The 21CXRM Palaeozoic project results are delivered as a series of reports and digital datasets for each area.

This report describes the stratigraphical correlation of Devonian and Carboniferous strata south of, and over, the Mid North Sea High (Quadrants 25-44) using both well and seismic data. It builds on the work of Cameron (1993a) and others, and uses lithostratigraphy to understand how facies vary across the area. A major outcome of this work is the detailed description of the Cleveland Group, the basinal correlative of the Scremerston, Yoredale and Millstone Grit formations within the offshore extension of the Cleveland Basin.

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 Devonian and Carboniferous strata in Quadrants 25–44 of the Mid North Sea High and adjacent areas, and integrates this with the adjacent onshore areas of the Midland Valley of Scotland and Northern England. Nine correlation panels (Section 4) were constructed across the region, tying in selected key wells in order to erect a framework for the Devonian and Carboniferous strata and to provide regional-scale seismic ties (Figure 1). The geological evolution of the offshore region has been interpreted in a number of key papers. The Pennsylvanian and Early Permian tectonostratigraphy in Quadrants 31 and 39 at the southern margin of the Central North Sea was described by Martin et al. (2002) and the Flora Field in Blocks 31/26a and 31/26c by Hayward et al. (2003). South of the Mid North Sea High, Collinson (2005) interpreted the depositional systems of the Mississippian and lower Pennsylvanian strata in Quadrants 41–43. Offshore, the lithostratigraphy of the Devonian to Permian rocks to the north of the Mid North Sea High is described by Cameron (1993b) and that to the south by Cameron (1993b), Bruce and Stemmerik (2003), and Kombrink et al. (2010). Cameron's (1993a) scheme for the upper Pennsylvanian rocks of Quadrants 41–44 was modified subsequently by Besly (2005). The Carboniferous stratigraphy in all of these areas has been summarised by Waters et al. (2011).

The onshore geology of the Devonian and Carboniferous of the Midland Valley of Scotland and Northern England has been studied extensively, with succinct modern summaries of the lithostratigraphy, palaeogeography and tectonic evolution provided by Chadwick et al. (1994), Browne et al. (1999), Read et al. (2002), Trewin and Thirlwall (2002), Waters and Davies (2006) and Stone et al. (2010). The onshore Devonian and 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 (Browne et al. 2003; Waters & Davies, 2006; Waters et al. 2007; Dean et al. 2011 and references therein).

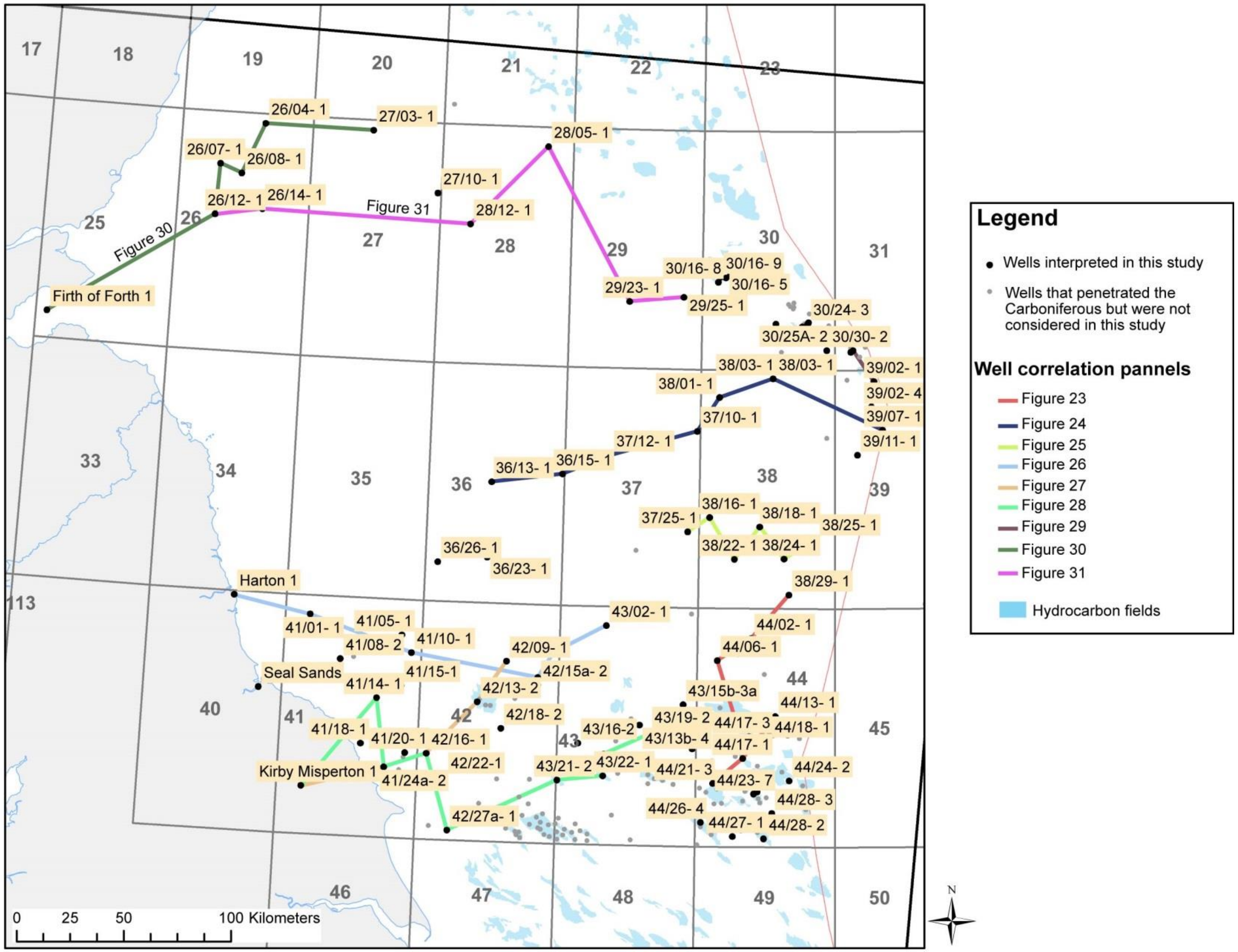

Figure 1 Location of wells and correlation panels that penetrate the pre-Permian strata and the subset which were studied in detail for this stratigraphical study.

The stratigraphical scheme used in this report is summarised in Figures 2 and 3 and broadly follows Waters et al. (2011) for the Carboniferous and Cameron et al. (1993a, b) for the Devonian. Though there are differences between the nomenclature used onshore and offshore, the formation names in the latter are used throughout this report. Figure 4 shows the correlation with the Dutch and Danish stratigraphy.

A few important amendments to the offshore stratigraphy result from the present work. Most significant is the recognition in Quadrants 41–44 of the basinal equivalents of the Fell Sandstone, Scremerston, and Yoredale formations within the offshore Cleveland Basin. The term Cleveland Group is used for this sequence, extending its previous use in the lower part of the Seal Sands Borehole (Johnson et al. 2011). The Cleveland Group is defined and described in Section 3.5. The presence of high-gamma mudrocks in the upper part of the group suggests a correlation with the Bowland Shale Formation of the Bowland – Hodder unit of the Craven Basin (Andrews 2013; Slowakiewicz et al. 2015).

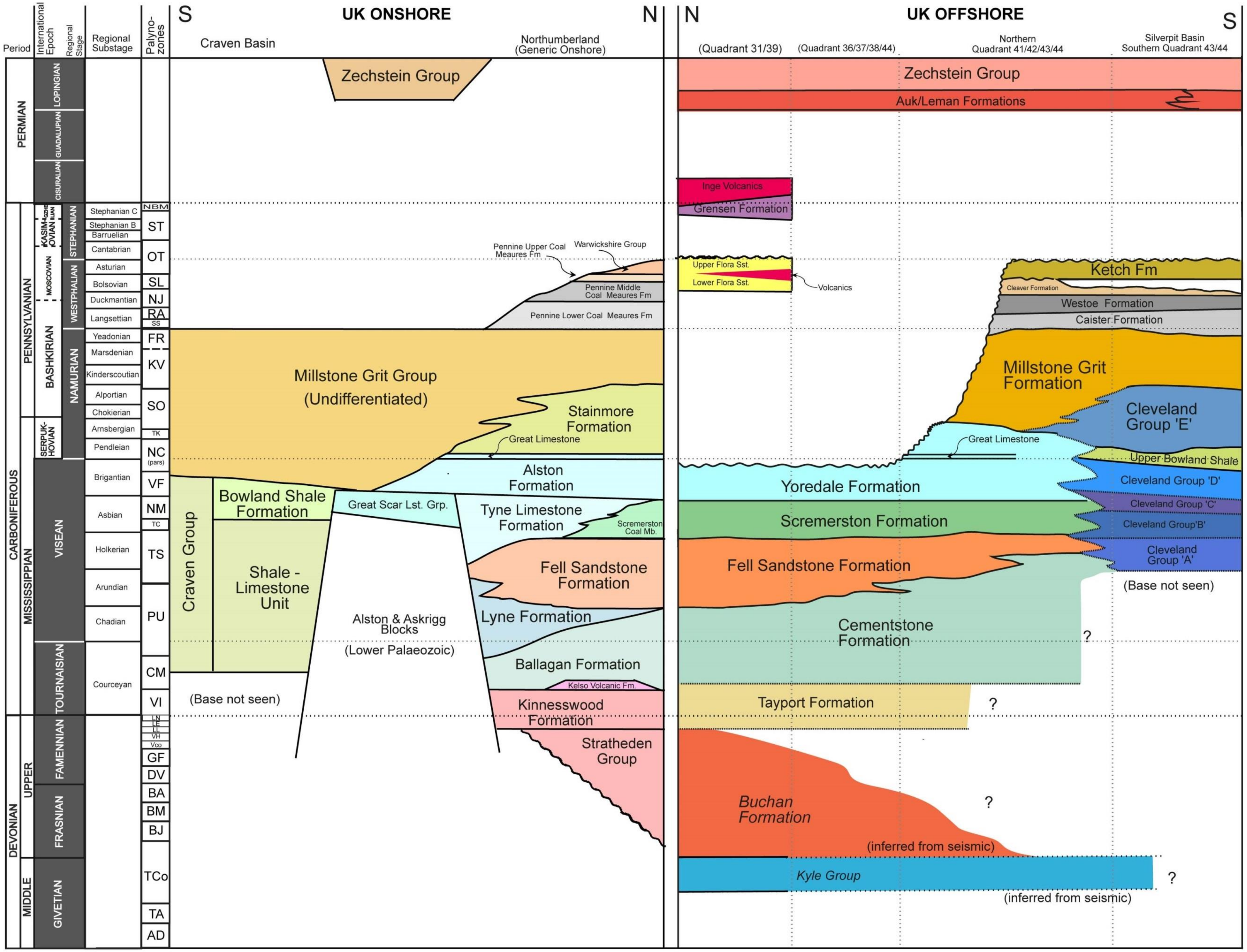

Figure 2 Schematic north – south cross-sections showing the relationships between the Carboniferous and Devonian strata of northern England and the Central North Sea

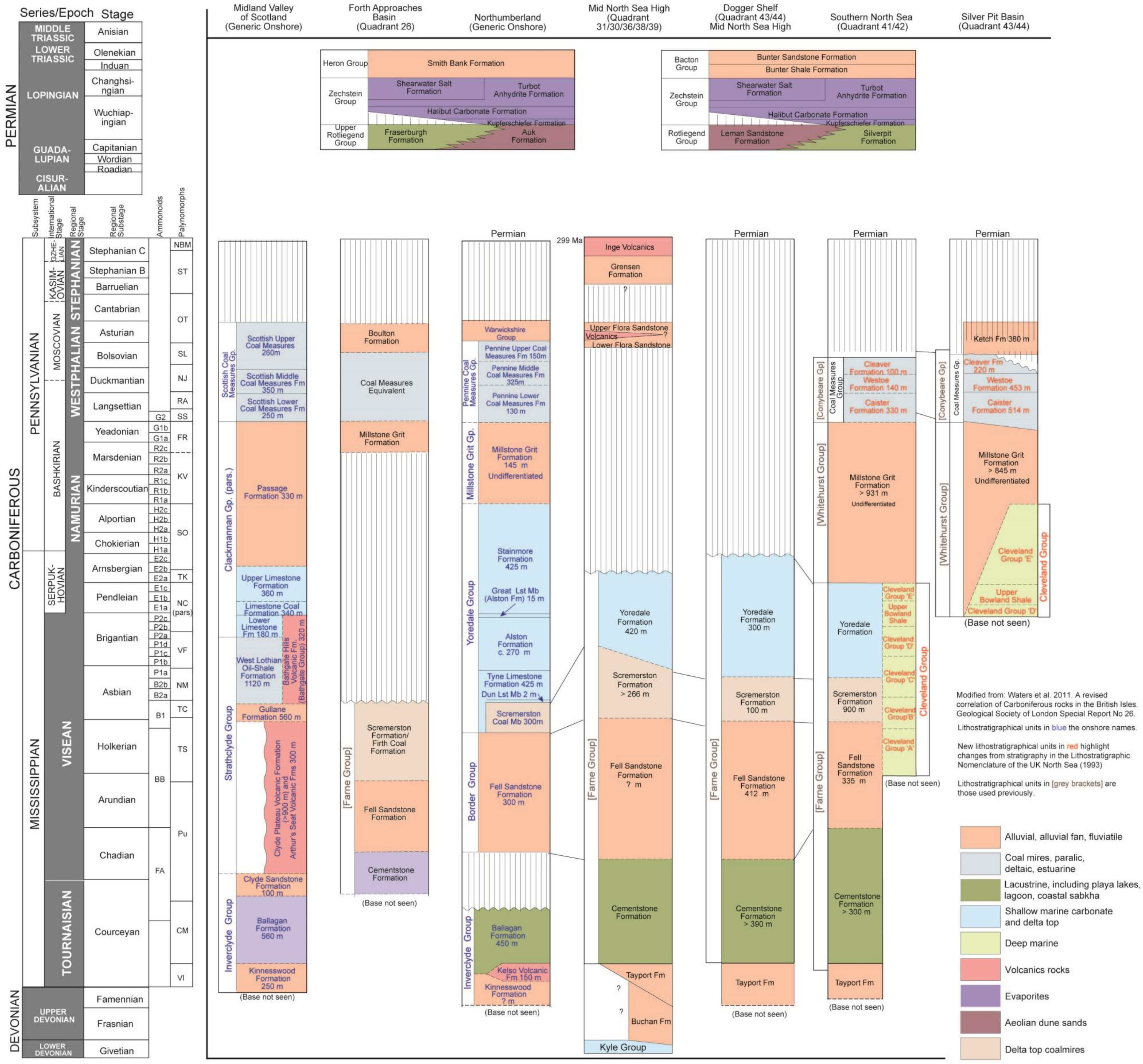

Figure 3 Carboniferous stratigraphical successions and correlation of the onshore UK and adjacent quadrants in the Central North Sea.

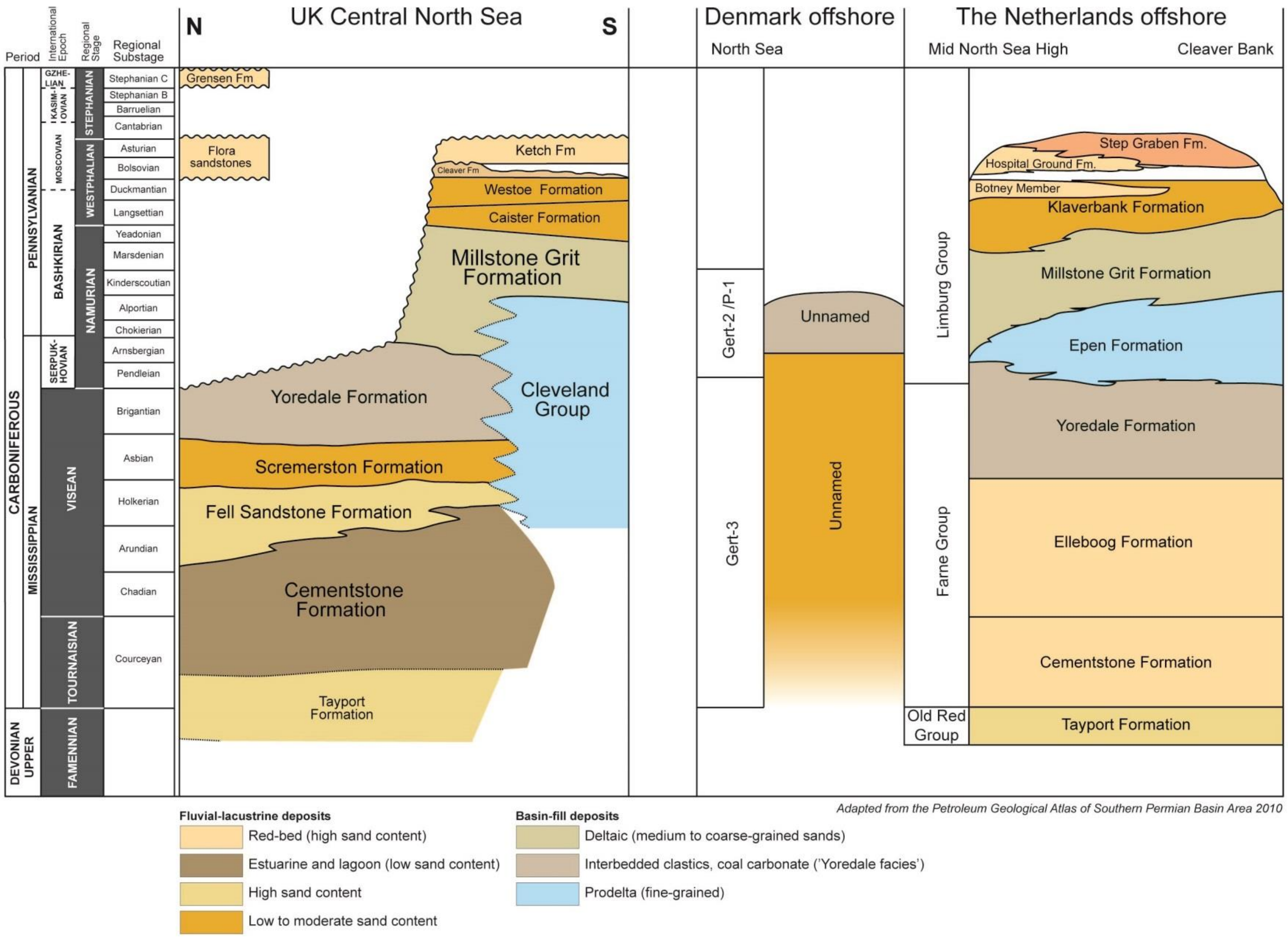

Figure 4 Correlation between the UK Central North Sea stratigraphy in this study and the Danish and Dutch sectors (modified after Kombrink et al., 2010).

1.1 DATA AND WORKFLOW

More than 230 wells have penetrated Devonian and Carboniferous rocks in Quadrants 25–44. However, the distribution is uneven, and many of the wells proved only a short succession of these strata. In the Forth Approaches Basin only three wells recorded significant thickness of rocks of this age, and none reached these strata in Quadrants 34–35 nor in the southern part of Quads 25–28 over the Mid North Sea High. A greater density of wells is present to the east and south of the region, particularly in the southern parts of Quadrants 43 and 44 containing the Southern North Sea Westphalian gas fields. Nine correlation panels were constructed using 91 wells selected for the thick successions of Devonian and/ or Carboniferous strata that they proved or as key ties to the seismic data (Figure 1).

A set of key onshore wells were selected to provide a link between the offshore and onshore stratigraphy. In the Midland Valley of Scotland the wells selected are: Firth of Forth 1 and Milton of Balgonie 1. In Northern England, three onshore wells were included: Seal Sands 1 (Johnson et al. 2011); Harton 1 (Ridd et al. 1970); and Kirby Misperton 1.

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, for example Collinson (2005) in Quadrants 41-44, 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 succession compared with what is known onshore. A list of the biostratigraphical reports used can be found in the picks spreadsheet (21CXRM_BGSWellTops_reinterpreted_biostrat_v2.xlsx). For the Carboniferous succession the biostratigraphic zonation scheme (ammonoids and palynology) 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 1).

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 Devonian Strata

In Quadrants 30, 37 and 38, composite logs show wells that penetrate 'Devonian' strata. However, these stratacommonly fail to provide biostratigraphical information and they are difficult to differentiate from Permian (Rotliegend) strata in the wells. Identification in wells typically relies on interpretation of the porosity and sonic properties from wireline logs and in identifying the position of the Variscan unconformity from the seismic data.

2.1 KYLE GROUP

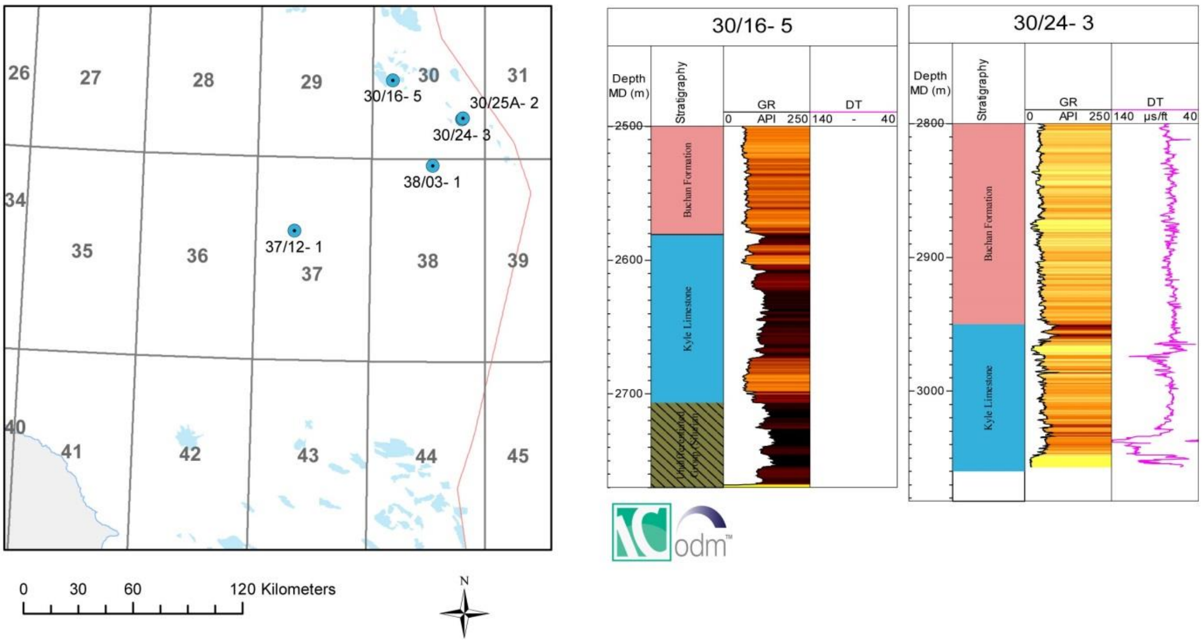

Figure 5. Map showing the distribution of wells where the Kyle Group has been interpreted, and selected logs from key wells that illustrate the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The oldest Devonian strata proved in wells in Quadrants 30, 37 and 38 east of the Mid North Sea High. These rocks are assigned to the Kyle Group, The name was introduced by Cameron (1993a) .

Geographical extent

The Kyle Group is proved in wells on the Auk Ridge and on the Dogger Granite High. It generates a distinct seismic reflector which can be correlated over large areas south and east of the Mid North Sea High (Arsenikos et al. this study).

Lithology

The Kyle Group is characterised by limestone units separated by shale and sabkha facies. Two limestone units are seen in well 30/16- 5. The limestone is dominantly bioclastic, containing tabulate and rugose corals, ostracods, brachiopods, bivalves, gastropods and crinoids (Marshall and Hewett 2003). In 38/03- 1 the group is at least 119 m thick, whereas in well 37/12- 1 it is at least 183 m thick.

Key Wells

The conformable top contacts of the Kyle Group are seen in wells 38/03- 1, 30/24- 3. The successions are dated by miospores in those wells. The base of Kyle Group is proved only in well 30/16-5.

Lower boundary

The base of the Kyle Group in well 30/16-5 rests unconformably on deformed Palaeozoic basement (Marshall and Hewett, 2003; Trewin and Bramwell, 1991). Seismic and well evidence suggests the Kyle Group is underlain by basement or granite on highs and Lower Devonian sedimentary rocks within basins.

Upper boundary

The top of the Kyle Group is conformable with the base of the overlying Buchan Formation (Marshall and Hewett, 2003; Cameron, 1993a). The boundary is taken at the top of the first siltstone underneath the deepest sandstone of the Buchan Formation.

Age

The Kyle Group is dated as Middle Devonian (Givetian), based on palynology and macrofossils (Bangal et al. 1978).

Correlation with onshore UK

The Kyle Group has no equivalent in the adjacent onshore area, as there the middle Devonian is missing.

2.2 BUCHAN FORMATION

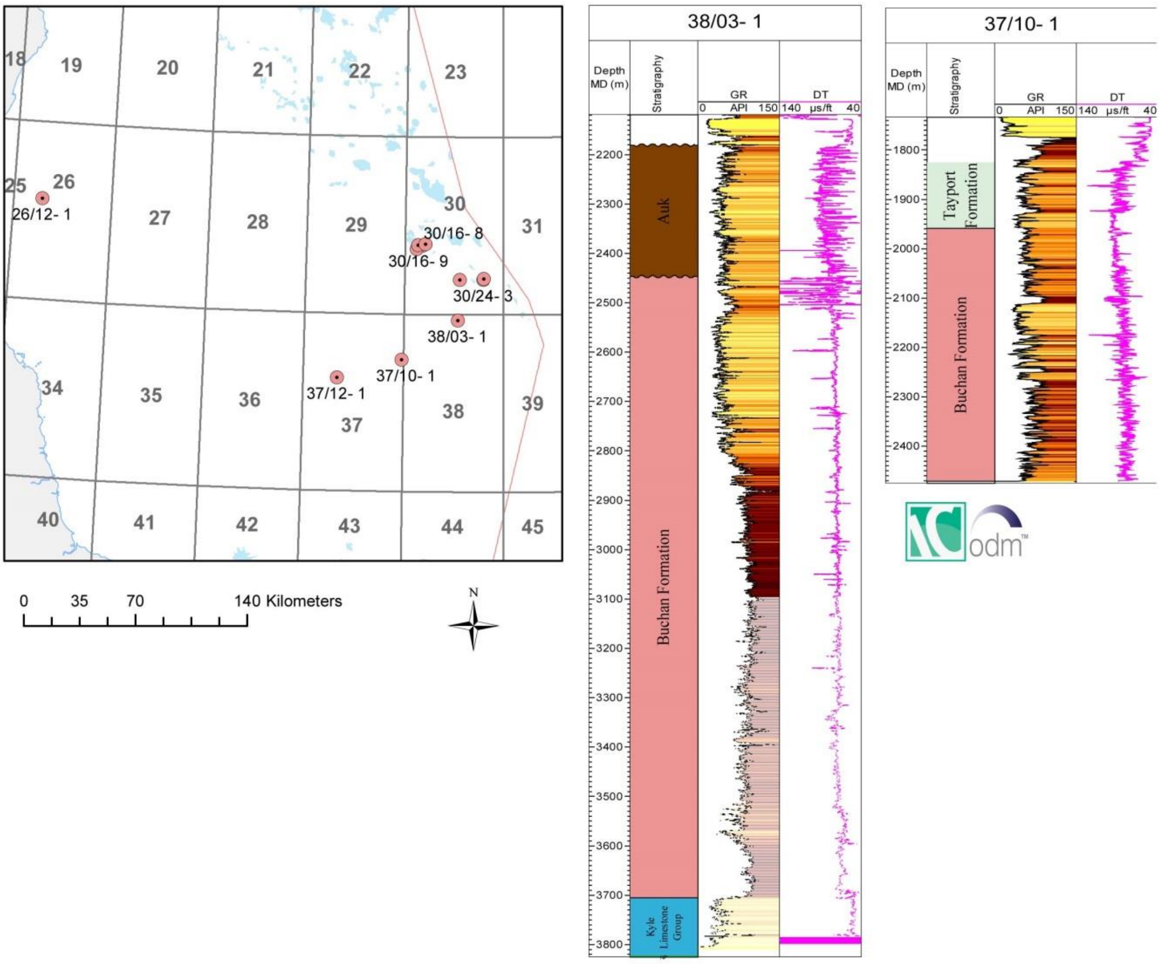

Figure 6 Map showing the distribution of wells where the Buchan Formation has been interpreted, and profiles of the key wells that illustrate the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Buchan Formation was defined by Cameron (1993a) for a sandstone-dominated unit of Late Devonian age that is thought to represent braid-plain and alluvial-plain environments (Marshall and Hewett 2003).

Geographical extent

The formation is seen in wells on the Auk Ridge and in the Forth Approaches, on the northern edge of the Mid North Sea High. It is known to extend north into the Orcadian Basin (Marshall and Hewett 2003).

Lithology

The Buchan Formation is largely composed of reddish brown, fine- to medium-grained sandstone, interbedded with thin beds of siltstone and mudstone (Cameron 1993a). The succession shows an increased gamma response with depth (e.g. well 38/03- 1) related to an increase in silt and mud content. The wireline log signatures lack the cyclicity seen in the Carboniferous successions.

Key Wells

The conformable basal contact of the Buchan Formation is seen in wells 38/03- 1, 30/24- 3, where it overlies the Kyle Group. The conformable upper boundary is only seen in well 37/10- 1 in the Central North Sea.

Lower boundary

The base of the formation is conformable with the top of the Kyle Group (Marshall and Hewett 2003; Cameron 1993a). In well 38/03- 1 the boundary is taken at the abrupt change from silty sandstone to limestone.

Upper boundary

The upper boundary of the formation grades into the Tayport Formation in well 37/10- 1. The top of the formation is taken at the top of the succession beneath a low sonic velocity unit corresponding to 36 m sandstone at the base of the Tayport Formation. In well 38/03- 1 there is a marked change in the character of the sonic log signature (Figure 6).

Age

The Buchan Formation has often proved barren palynogically and there are few determinations in Quadrants 25-44 (Cameron, 1993a). Frasnian and Famennian palynomorphs were reported from samples from wells 38/03-1 and 38/29- 1 respectively (Marshall and Hewett 2003). However, farther north, the Buchan Formation has been shown to span the uppermost Middle Devonian and Lower Mississippian (Marshall and Hewett 2003).

Correlation with Onshore UK

The onshore equivalent of the Buchan Formation in southern Scotland is the Stratheden Group. Correlation with the onshore succession in northern Scotland will be explored more fully in the report on Quadrants 8-23.

2.3 TAYPORT FORMATION

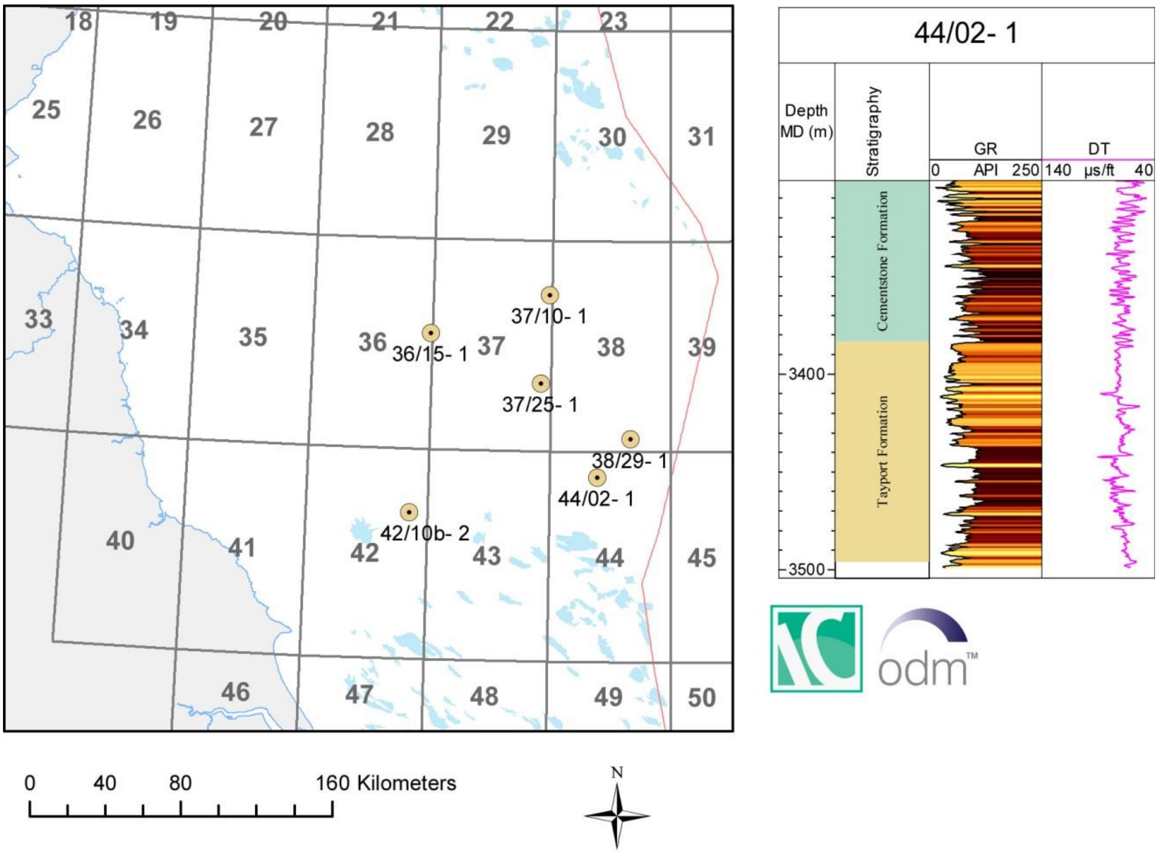

Figure 7. Distribution map of the wells proving the Tayport Formation and a profile of the key well that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The name Tayport Formation was introduced by Cameron (1993a) for a unit which is widespread around the Outer Moray Firth, stratigraphically below the Firth Coal Formation. Cameron (1993a) suggested that the Tayport Formation extends south and east of the Mid North Sea High, beneath the Cementstone Formation.

Geographical extent

The Tayport Formation is proved in wells in quadrants 36, 37, 38, 42 and 44 (Figure 7) near the Dogger Granite High. However, it is known to extend into the Dutch sector and may be present underneath the Cementstone Formation.

Lithology

South of the Mid North Sea High, the Tayport Formation is defined in well E06-01 in the Dutch sector, where it is described as 'red to red-brown and grey claystone and siltstone, interspersed with well developed sandstone beds'. The dominant lithology seen in the Tayport Formation is brown and red shale, and mudstone with grey mica-rich siltstone. It also contains sandstone bodies between 2-5 m in thickness which are interbedded with the shales and siltstones. The presence of thin limestone beds has also been inferred from the wireline logs.

Key wells

The key well is 44/02-1 which proves the upper contact of the Tayport Formation. It is also seen in well E06-01 in the Dutch sector.

Lower boundary

The conformable lower boundary in well 37/10-1 is taken at the base of a 36 m thick unit with low sonic velocity interpreted as sandstone.

Upper boundary

The top of the Tayport Formation in 44/02- 1 is taken at the base of a sonic-log spike corresponding to the lowest dolostone bed of the overlying Cementstone Formation. This is the only known proving of this boundary south of Mid North Sea high in UK waters. The upper boundary of the Tayport Formation is also seen in the Dutch well E06-01, where it is taken below the first occurrence of limestone beds (Van Adrichem Boogaert & Kouwe, 1993-1997).

Age

The Tayport Formation is inferred to be Strunian (uppermost Famennian) in age in well E06-01 in the Dutch sector (Van Adrichem Boogaert & Kouwe, 1993-1997). This is based on the occurrence of the palynomorphs *Spelaeotriletes lepidophytus* and *Raistrickia variabilis* which are considered to be Strunian (J E A Marshall pers. comms.). In 37/10-1 an earliest Tournaisian age has been assigned on palynomorphs (McLean 2013).

In the Forth Approaches Basin, the Tayport Formation has been identified previously in well 26/7- 1 by Cameron (1993) and Bruce and Stemmerik (2003). This is now interpreted as the Fell Sandstone Formation based on its mid Holkerian (V3a) to Chadian (V1a) age.

Correlation with Onshore UK

The Tayport Formation correlates directly with the Kinnesswood Formation onshore, though none of the thick, hardpan calcrete horizons that are characteristic of the Kinnesswood Formation adjacent to the Southern Uplands (Browne et al. 1999) is seen in the offshore wells. The Kinnesswood Formation onshore is known to continue in to the Carboniferous in the Midland Valley of Scotland (Browne et al. 1999). In Northumberland, however, it is believed that the Kinnesswood Formation may be latest Devonian in age (Smithson et al. 2012).

3 Carboniferous Strata

3.1 CEMENTSTONE FORMATION

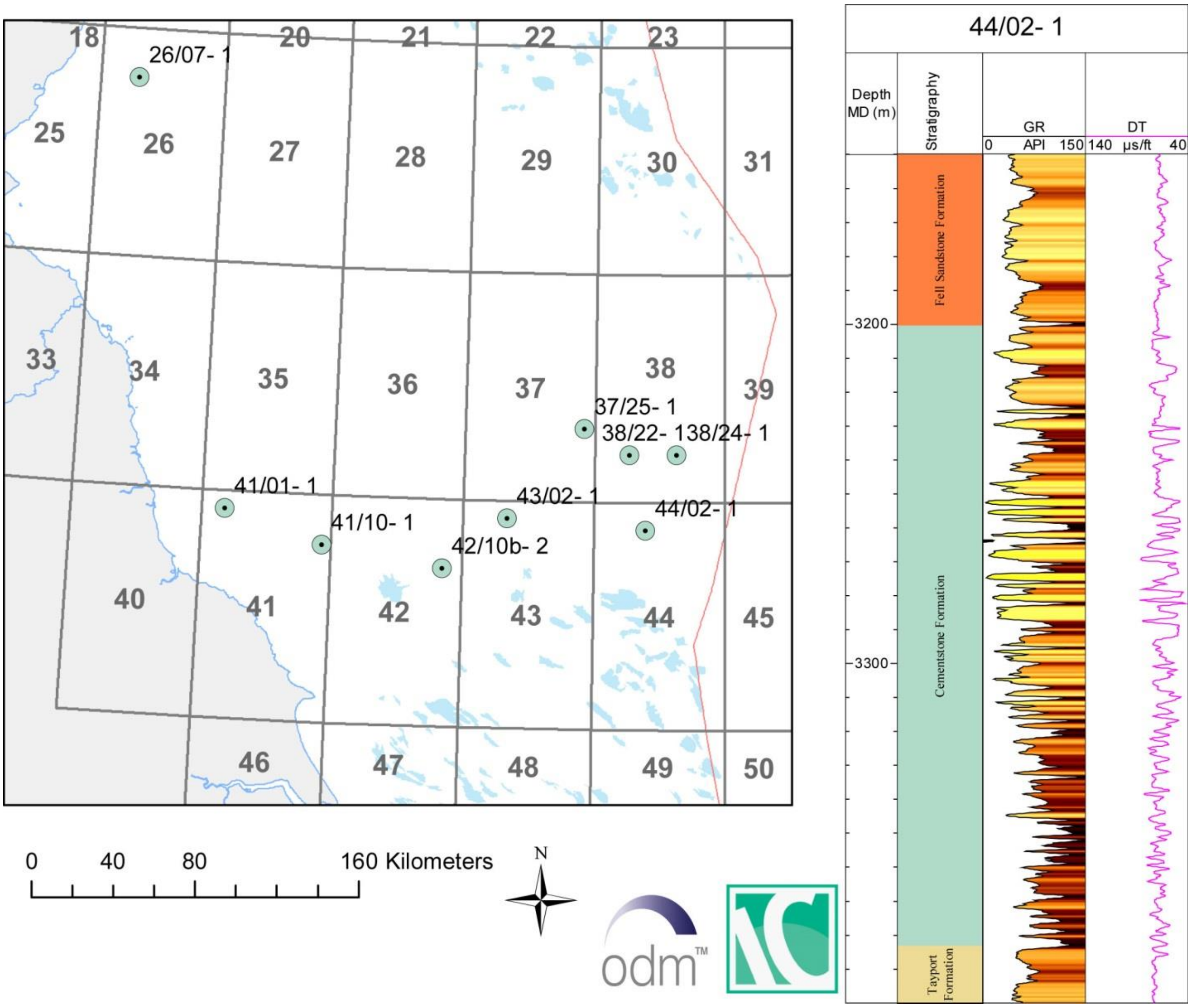

Figure 8 Map showing the distribution of the wells where the Cementstone Formation has been interpreted, and the profile of a key well that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Cementstone 'group' has been applied onshore in Northern England since the 19th century to a succession of alternating mudstone, sandstone, and dolomitic micrite which are referred to as cementstone. Cameron (1993a) applied this to a similar succession offshore that lies beneath the Fell Sandstone Formation. Cameron's definition and that of Bruce and Stemmerik (2003) are followed in the current study.

Geographical extent

The formation is recorded in wells around southern margin of the Mid North Sea High (Figure 8). It is also found in the base of well 26/07- 1 in the Forth Approaches Basin.

Lithology

The Cementstone Formation is composed of red/brown and green/grey siltstone and thin, fine- to coarse-grained sandstones, with dolostone and limestone beds between 1 and 4 m thick. The gamma log signature varies abruptly, alternating between low and high gamma values; bed thickness rarely exceeds 5 m, reflecting the thinly interbedded character. The thickness of the Cementstone Formation is from 100 to 500 m.

Key well

The conformable top and basal contacts of the Cementstone Formation occur in well 44/02- 1.

Lower boundary

The base of the Formation in well 44/02- 1 is taken at a sonic-log spike corresponding to the lowest dolostone bed upon a succession dominated by sandstone. This is the only known penetration of this boundary south of the Mid North Sea High in UK waters, but the formation is also present in the Dutch well E06-01.

Upper boundary

The top of the formation is taken underneath the first thick sandstone of the Fell Sandstone Formation. Onshore this contact is an erosion surface in part but conformable elsewhere (Dean et al. 2011).

Age

The Cementstone Formation is the oldest wholly Carboniferous unit within the study area and has been dated palynologically as Tournaisian to lower Visean in age. Its age has been proved biostratigraphically in wells 38/22- 1, 41/01- 1, 43/02- 1 (Cater et al. 1967; Mahdi 1992).

Correlation with onshore UK

The onshore correlatives of the Cementstone Formation are the Ballagan and Lyne formations of the Tweed and Northumberland basins (Waters, 2011). The Lyne Formation has the more marine character with limestones 1-10 m thick, compared with the Ballagan Formation which typically contains argillaceous dolostones generally less than 1 m thick. Offshore, the term Cementstone Formation is used to refer to the aggregate of both onshore units.

3.2 FELL SANDSTONE FORMATION

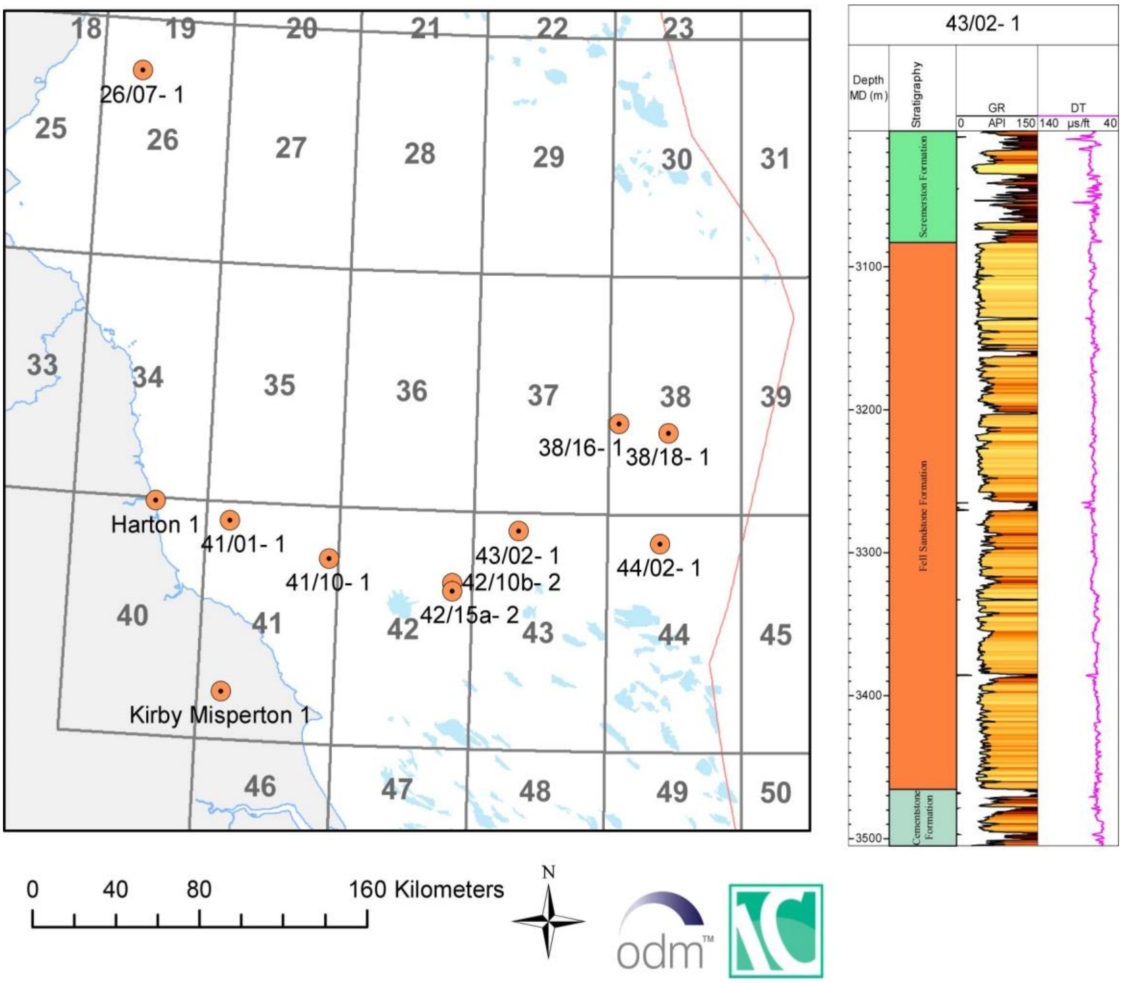

Figure 9: Map showing the distribution of wells where the Fell Sandstone Formation has been interpreted, and the profile of a key well that illustrates the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Fell Sandstone Formation has been applied in Northumberland (north-east England) and Berwickshire (south-east Scotland) since the 19th century to a thick unit of predominantly cross-stratified coarse-grained sandstone overlying the Cementstone Formation. The definition of the Fell Sandstone in the current study has not changed in from that of Cameron (1993a), and Bruce and Stemmerik (2003).

Geographical extent

The formation is recorded across Quadrants 26, 37, 38, 40, 41, 42, 43, and 44.

Lithology

The Fell Sandstone Formation is typically characterised by massive sandstone units up to 50 m thick, interbedded with units up to 20 m thick of siltstone and mudstone. In some wells (e.g. 26/07- 1) the succession comprises clean sandstone with only thin intercalations of siltstone and mudstone, elsewhere (42/10b- 2) the succession is more heterogeneous. Across the study area, the formation thickness varies from *c.* 418 m in 42/10b- 2 to about 60 m in 41/10- 1.

Key Well

The conformable top and basal contacts of the Fell Sandstone Formation have been observed in well 42/10b- 2.

Lower boundary

The base of the Fell Sandstone Formation is taken at the abrupt change from thick sandstone units to interbedded sandstone, mudstone and limestone of the underlying Cementstone Formation. There is a distinct change in wireline log character.

Upper boundary

The top of the formation is taken at the top of the highest thick sandstone unit below a succession dominated by alternations of mudstone, sandstone and coal of the Scremerston Formation.

Age

Palynological evidence from wells 41/01- 1, 43/02- 1 and 42/15a- 2 indicates that the Fell Sandstone Formation is Chadian (Pu Biozone) to earliest Asbian (TS Biozone). Onshore, the base of the Fell Sandstone Formation is diachronous, becoming generally younger toward the southwest (Stone et al. 2010).

Correlation with onshore UK

The Fell Sandstone Formation is equivalent to its onshore namesake.

Remarks

The Fell Sandstone Formation is interpreted to be the deposit of a major sandy braided-river system (Turner and Munro 1987), formed of stacked multi-storey channel fills and separated by mudstone intervals. The source of the braided river system is from the north-east (Robson, 1956) (see Section 5.2).

A sandstone body of Holkerian age beneath the Cleveland Group at the base of the Kirby Misperton 1 well has been interpreted in the current study as possibly the Ashfell Sandstone, rather than the Fell Sandstone. The Ashfell Sandstone crops out across much of northern England and is regarded as the distal equivalent of the Fell Sandstone and is of a different facies.

3.3 SCREMERSTON AND FIRTH COAL FORMATIONS

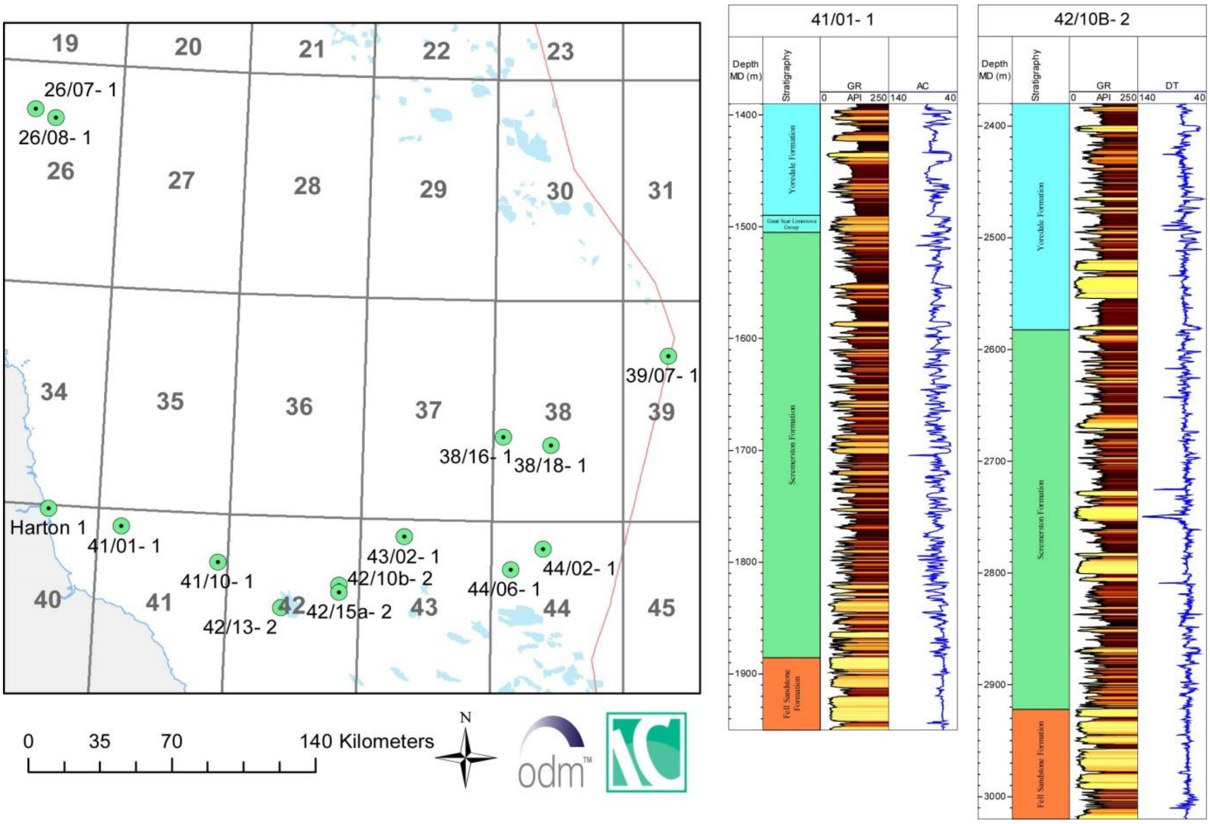

Figure 10: Map showing the distribution of the wells where the Scremerston Formation has been interpreted, and the profile of key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The historical onshore term Scremerston Coal Group was used offshore by Leeder and Hardman (1990) for Lower Carboniferous ‘coal measures’ encountered in the Southern North Sea. The unit was renamed the Scremerston Formation south of the Mid North Sea High by Cameron (1993a). Equivalent facies in the Forth Approaches Basin are known as the Firth Coal Formation (Cameron, 1993b).

Geographical extent

The Scremerston Formation is recorded from Quadrants 37, 38, 39, 40, 41, 42, 43, and 44. It is likely to be continuous in extent from the Northumberland coast across the Mid North Sea High and along its south-eastern margin (Cameron, 1993a). The Firth Coal Formation also occurs in the Forth Approaches Basin and has been proved in wells 26/07- 1 and 26/08- 1.

Lithology

The Scremerston Formation is identified by the presence of coal-rich intervals within a mudstone-dominated sequence, with alternations of sandstone, siltstone and some thin limestone or dolostone beds. Upward coarsening sequences are sometimes present within the upper parts of the formation, but are less cyclic in nature than the overlying Yoredale Formation. The sandstone units probably include both single and stacked channel fills. Homogeneous dark grey and black mudstones generate a uniformly high gamma-log response. Coals are up to 3 m thick in exceptional cases (Cameron, 1993b).

South of the Mid North Sea High the thickness of the Scremerston Formation varies across the study area, from about 90 m in 44/02- 1 to approximately1 km in 41/10- 1. The average is about 300 m. In the Forth Approaches the formation is 551 m thick in well 26/7- 1 and 688 m thick in 26/8- 1.

Key Wells

The conformable top and basal contacts of the Scremerston Formation have been observed in wells 41/01- 1 and 42/10b- 2.

Lower boundary

The base of the Scremerston Formation is taken at the change from the mudstone- and coal-dominated succession to the dominantly sandstone unit of the underlying Fell Sandstone Formation. Near the base of well 26/8- 1 there are several thick sandstones which may, along with the palynological age zonation, indicate downward transition to the Tayport Formation, equivalent to the Fell Sandstone in this area.

Upper boundary

The top of the Scremerston Formation is picked at the top of clastic sedimentary succession beneath the base of the lowest significant marine limestone bed in the overlying Yoredale Formation. In most of the wells the formation is overlain by the Yoredale Formation. However, in Harton 1 and in near-shore wells such as 41/01- 1, the Scremerston Formation is overlain by a thin development of limestones with subordinate siltstone and sandstone which are equated with the onshore Great Scar Limestone Group.

Age

A late Holkerian to Asbian age for the Scremerston Formation is proved palynologically in well 41/01- 1, but elsewhere south of the Mid North Sea High it is Asbian. The two wells in the Forth Approaches which penetrate the Scremerston/Firth Coal Formation have yielded palynomorphs of Upper Arundian and Holkerian to upper Asbian age (Mclean and Neves, 1988).

Correlation with onshore UK

The Scremerston Formation is equivalent to the onshore Scremerston Coal Member of the Tyne Limestone Formation (Waters, 2011). The Firth Coal Formation in the Forth Approaches is equivalent in age to the lower part of the Strathclyde Group in the Midland Valley of Scotland. It equates with the fluvio-deltaic to marine Sandy Craig, Pittenweem, Anstruther, Fife Ness, Aberlady and Gullane formations of Fife and the Lothians, and to the dominantly lacustrine and organic-rich West Lothian Oil-Shale Formation. The coals and mudstones within this formation represent an important source rock.

Remarks

The Scremerston Formation is interpreted to represent a range of depositional environments including fluvio-deltaic, lacustrine, wetland and marine-influenced bay deposits associated with a major deltaic system (Leeder and Boldy, 1990; Leeder et al., 1989).

The onshore wells Seal Sands 1 and Harton 1, along with the nearby offshore wells 41/08- 2 and 41/01- 1 contain a thick succession of upper Asbian limestone and mudstone units that represent the eastern extent of the carbonate platform deposits of the Great Scar Limestone that developed over the Alston and Lake District blocks during the Asbian. The palaeogeography of the Scremerston Formation is described further in Section 5.3.

3.4 YOREDALE FORMATION

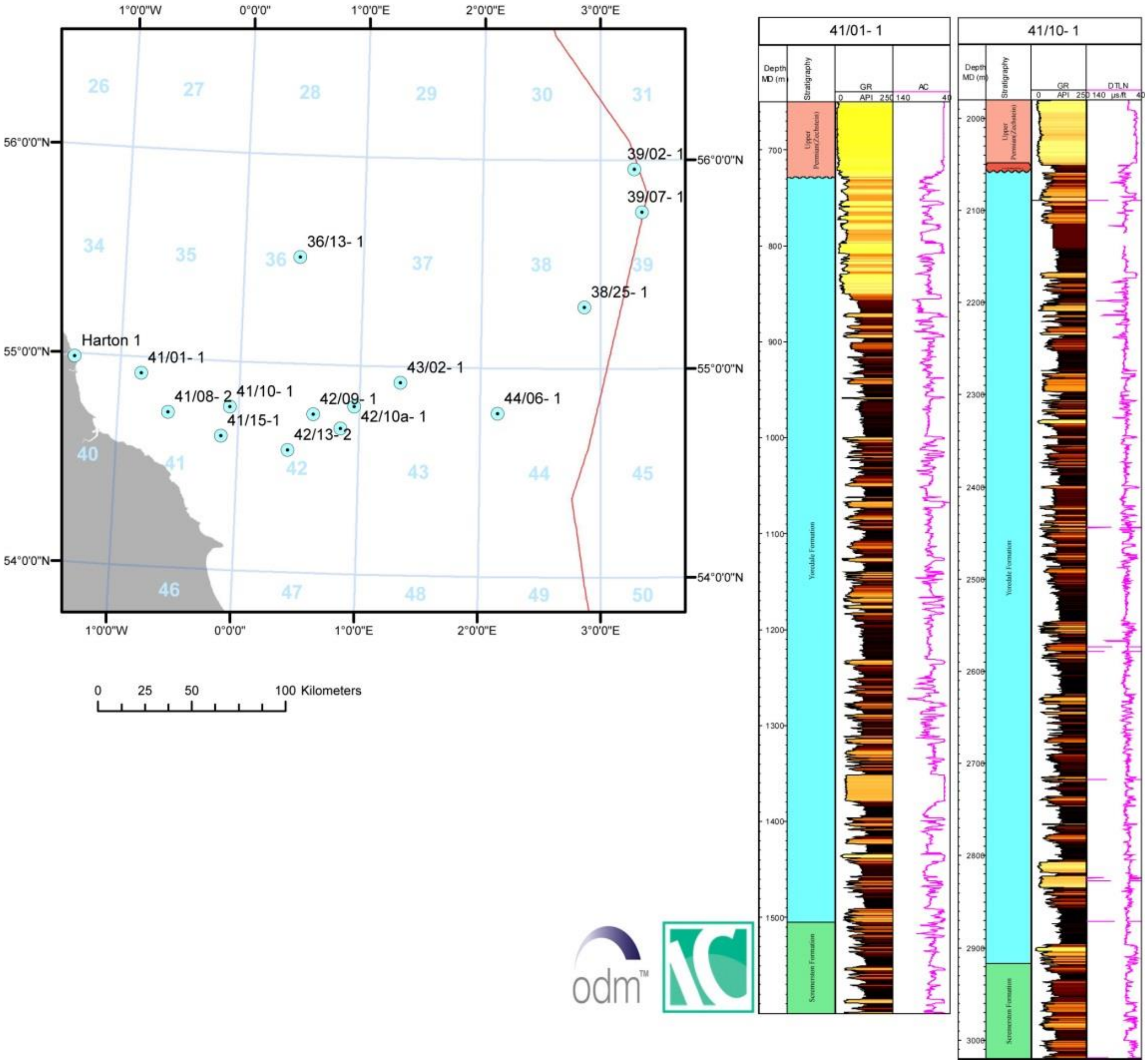

Figure 11: Map showing the distribution of the wells where the Yoredale Formation has been proved within the study area, and profiles of the key wells that illustrate the principal character of the wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Yoredale Formation was introduced by Cameron (1993a) for an upper Asbian to Brigantian and lower Namurian fluvio-deltaic succession with significant limestone beds.

Geographical extent

The Yoredale Formation is recorded across Quadrants 36, 38, 39, 40, 41, 42, 43, and 44. Its depositional extent is likely to have been continuous from northern England across the Mid North Sea High.

Lithology

The Yoredale Formation comprises a repeated succession of 'Yoredale cycles', commencing with a basal marine limestone, overlain by an upward coarsening succession of marine mudstone and sandstone, and capped by a seatearth palaeosol (a grey or whitish clay rock containing fossilized plant roots and occurring beneath coal seams) and coal. Individual limestones are widespread in occurrence and can be correlated across the study area. Some fining upward cycles are also present. The lower part of the Yoredale Formation locally contains thick multi-storey channel sandstones interpreted to be infilled palaeovalleys (Collinson, 2005). Such distinctive sandstone units are encountered in wells 41/10- 1, 42/10b- 2 and 43/02- 1, and referred to as the Whitby Sandstone Member. This unit is distinguished on wireline logs by two thick units of sandstone separated by a mudstone interval. The geometry of these sandstone bodies is not known: they may represent a very wide, single fluvial channel system, or separate, narrow channel fills.

Key Wells

The conformable top and basal contacts of the Yoredale Formation have been proved in the Harton 1 well. Wells 41/01- 1 and 41/10- 1 display the basal conformable contact with the Scremerston Formation. Harton 1 is the only well to prove the full thickness of 875 m for the Yoredale Formation, but across northern England the thickness is known to vary significantly between the Alston Block and Northumberland Basin (Stone et al., 2010). Offshore, the preserved thickness is from 150 m to at least 950 m thick.

Lower boundary

The base of the Yoredale Formation is picked at the base of the lowest substantial marine limestone (equivalent onshore to the Dun Limestone) above the coal-rich Scremerston Formation.

Upper boundary

The top of the Yoredale Formation is picked at the top of the highest marine limestone bed at the base of the Millstone Grit Formation. However, in most wells, the Yoredale Formation is overlain unconformably by Permian strata. In wells that penetrate the formation in Quadrant 39, the Yoredale Formation is overlain by the Grensen Formation (wells 39/02- 1 and 39/07- 1).

Age

The Yoredale Formation is late Asbian, and Brigantian to early Namurian in age, based on palynological data from wells 38/25- 1, 39/07- 1, 41/01- 1, 42/09- 1, 43/02- 1 and 44/06- 1.

Correlation with onshore UK

The Yoredale Formation is equivalent to sedimentary rocks in northern England comprising stacked sequences of Yoredale cycles (Cameron 1993a). This includes the upper part of the Tyne Limestone Formation (above the Scremerston Coal Member), and the Alston and Stainmore formations (Waters et al. 2007). The Stainmore Formation differs from the Alston Formation by containing generally thinner limestones than those in the Alston Formation and an increasing proportion of fining-upward parasequences. The base of the Stainmore Formation is taken at the base of a siliciclastic sedimentary unit immediately overlying the Great Limestone. At about 20 m, the Great Limestone is the thickest of the Alston Formation limestones. A comparably thick limestone is seen in some wells offshore (e.g. 44/06- 1) and is equated with the Great Limestone in Figure 22. Older northern England terminology of Lower, Middle and Upper Limestone Groups is used in Collinson's (2005) interpretation of this succession in Quadrants 42-44. Comparison of these names with those used in this report is provided by Figure 38 of Stone et al. (2010).

Remarks

Compared with the Scremerston Formation, the Yoredale Formation contains thicker limestones and the common presence of coarsening-upwards parasequences. Though present at outcrop, typically beneath the limestones, the thin coals within the Yoredale Formation are mostly below wireline logging resolution.

The Yoredale Formation is a continuation of the deltaic conditions that became established in Asbian times with the Scremerston Formation. Both formations comprise Yoredale facies, with the Scremerston Formation representing more landward environments. The cyclic character of the Yoredale Formation resulted from fluctuations in sea level forming an extensive carbonate shelf during high-stands with deposition of the limestones with subsequent filling of the accommodation space as the delta system re-exerted its influence. It is thought that the sea level changes were the far-field effect of continental glaciation (Stone et al, 2010 and references therein).

3.5 CLEVELAND GROUP

The stratigraphical term Cleveland Group was introduced by Johnson et al. (2011) for the thick middle Visean shale-rich succession proved in Seal Sands No. 1 well. The use of the term is expanded in this report to describe the succession of rocks that are equivalent in age to the Scremerston and Yoredale formations, but which differ from them in lithofacies (Figure 2 and Figure 3). Geographically, the Cleveland Group strata occur within the Cleveland Basin. The Group is distributed across the southern half of Quadrants 41 to 44, and Cameron (1993a) thought it likely that these strata extend south into Quadrants 48, 49, 53 and 54. These rocks are interpreted to have been deposited in a basin beyond the southern margin of the Yoredale delta front and represent the distal deposits shed off the delta front; the sandstone and limestone units may be turbiditic.

The Cleveland Group is typified by thick successions of fine-grained lithologies of siltstone and mudstone, interbedded with thin units of sandstone and limestone. The succession lacks the thick limestones and characteristic upward-coarsening parasequences of the Yoredale Formation, and the many coals that are typical of the Scremerston Formation. In the upper part of the group a high-gamma shale unit has been termed the Bowland Shale Formation by Cameron (1993a). The wireline log characteristics are similar to the Upper Bowland Shales seen within the Bowland–Hodder unit of the onshore Craven Basin, providing a critical link with that basin (Andrews, 2013).

Onshore, Upper Bowland Shales is a long-used term for dark grey mudstone of Pendleian age in the Craven Basin, but is now subsumed within the Bowland Shale Formation of longer duration. The Upper Bowland Shales name is used in the Cleveland Basin informally to emphasise the similarity of lithology in the two basins. Cameron's (1993a) usage is discontinued to avoid confusion with the wider definition of the same term in the Craven Basin.

Though Johnson et al. (2011) divided the Cleveland Group in the Seal Sands No. 1 well, the succession there is incomplete and located close to the margin of the basin. By contrast, Kirby Misperton 1 is located towards the centre of the basin and proved a total thickness of around 1400 m for the Cleveland Group; it is used in this report as the key well for the Cleveland Group.

There is significant lateral lithofacies variation in the group and in the informal divisions proposed in this report are based on gross characteristics of the units. These may require adjustment if more data become available.

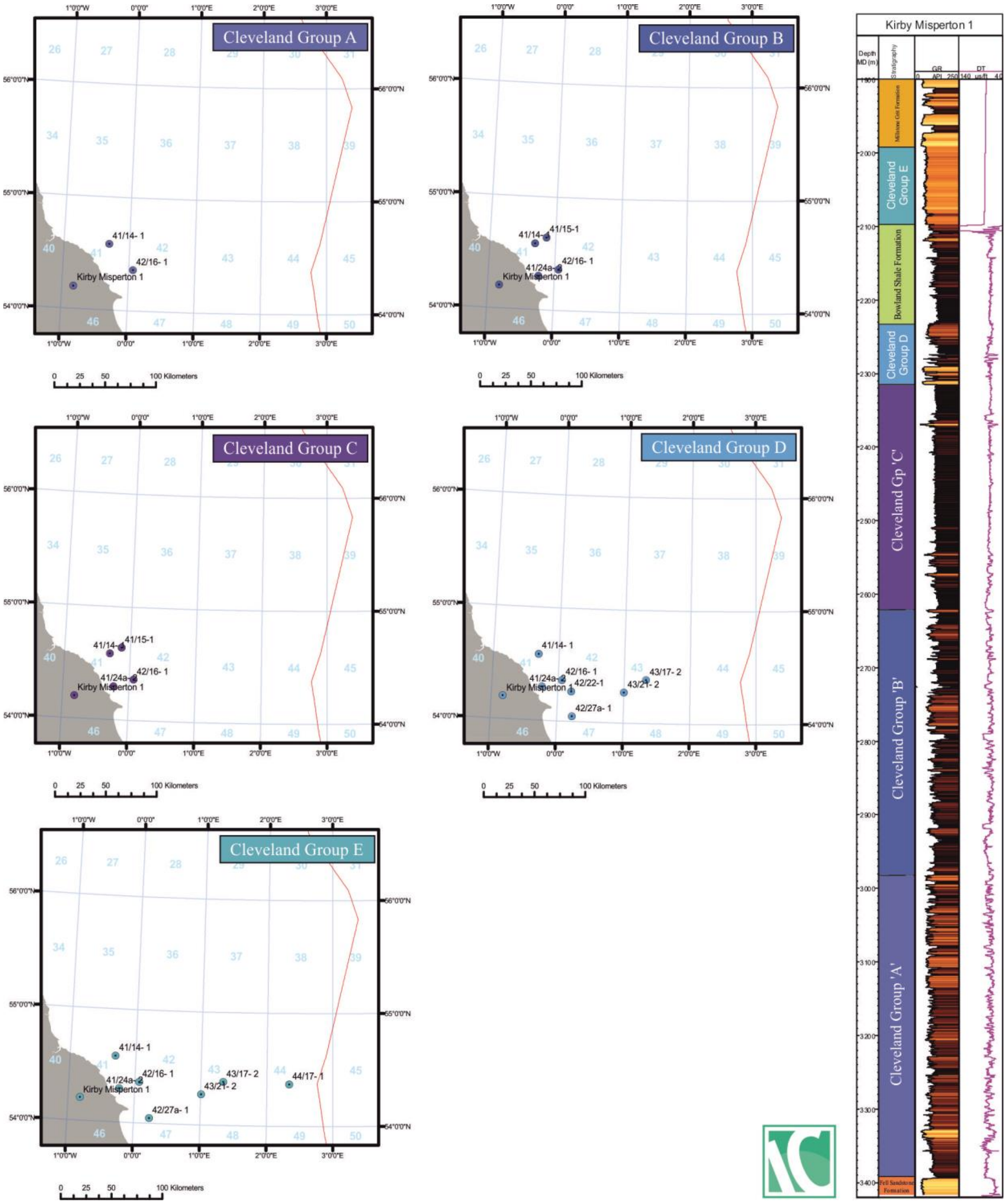

Figure 12: Map showing the distribution of wells where the Cleveland Group has been identified, and the key well profile that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit in support of further unit subdivision.

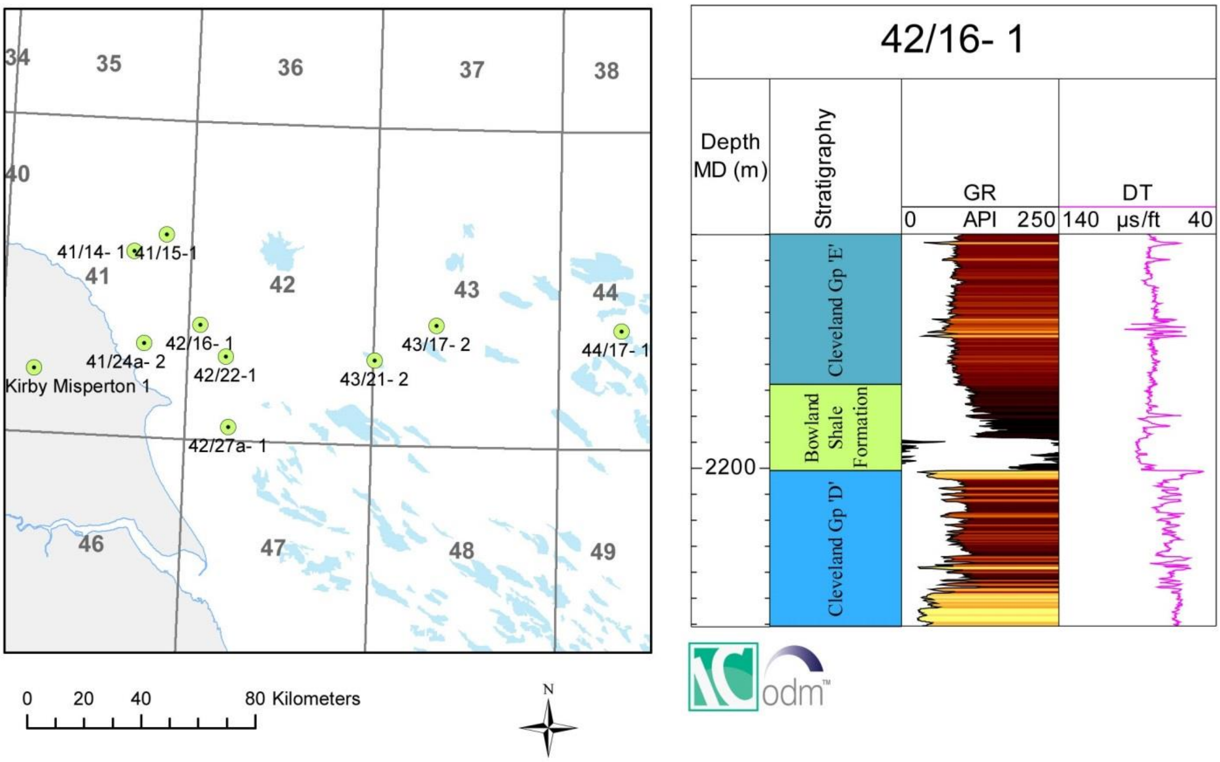

Figure 13: Map showing the distribution of the wells where the Upper Bowland Shales has been identified within this study, and the profile of the key well that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

3.5.1 Cleveland Group A

Lithology

Cleveland Group A is characterised by sandstone and siltstone with thin mudstone and limestone units. Some upward-coarsening cycles are present (e.g. well 42/16- 1).

Lower boundary

The base of Cleveland Group A is encountered in Kirby Misperton 1, where its base is taken at base of the shale above the sandstone at the base of the well which has been previously assigned to the Fell Sandstone Formation, but more likely with its more distal correlative, the Ashfell Sandstone.

Upper boundary

The top of the Cleveland Group A is taken at the top of the first sandstone unit encountered beneath the homogenous mudstone/siltstone succession of the Cleveland Group B.

Age

Palynomorphs from wells 41/14- 1, and Kirby Misperton 1 indicate that Cleveland Group A lies within the Arundian to Brigantian interval.

3.5.2 Cleveland Group B

Lithology

Cleveland Group B comprises mudstone and siltstone with sporadic thin units of limestone and sandstone. The unit is characteristically homogeneous, except in Kirby Misperton 1 which includes significant sandstone and limestone; furthermore there are thin intervals of high-gamma mudstone.

Lower boundary

The base of the Cleveland Group B is taken at the base of siltstone overlying the uppermost sandstone unit of Cleveland Group A.

Upper boundary

The top of the Cleveland Group B is taken below the base of the lowermost sandstone unit in the overlying Cleveland Group C.

Age

Palynomorph assemblages from wells 41/14- 1, and Kirby Misperton 1 indicate an Arundian to Brigantian age for the Cleveland Group B.

3.5.3 Cleveland Group C

Lithology

In general, Cleveland Group C is composed of mudstone and sandstone, with units of the latter typically less than 50 m thick. By contrast, in Kirby Misperton 1, Cleveland Group C is dominated by a continuous mudstone succession, intercalated with thin beds of limestone and sandstone. In Quadrant 41 the succession superficially resembles the Yoredale Formation, but there are fewer limestones and upward-coarsening parasequences. These wells may have penetrated the transition zone from the Yoredale delta front into the Cleveland Basin.

Lower boundary

The base of the Cleveland Group C is taken at the base of a sandstone/siltstone unit above the mudstone-dominated Cleveland Group B.

Upper boundary

The top of Cleveland Group C is taken below the base of the most significant sandstone body within the overlying Cleveland Group D group.

Age

Palynomorphs from Cleveland Group C in wells 41/14- 1, 41/24a- 2 and Kirby Misperton 1 indicate an Arundian to Brigantian age for the unit.

3.5.4 Cleveland Group D

Lithology

Cleveland Group D is characterised by thick units of sandstone with subordinate interbedded mudstone, siltstone and some limestone. It is the most sandstone-rich of all the Cleveland Group units. At the top of the unit is a distinctive, thin unit comprising sandstone capped by limestone or calcareous sandstone. The thickness of the unit varies from 59 m in well 41/24a- 2 to 615 m in well 43/17- 2.

Lower boundary

The base of Cleveland Group D is taken at the base of the most significant sandstone body within the group, above the siltstone/mudstone-dominated Cleveland Group C.

Upper boundary

The top of Cleveland Group D is taken at the top of a limestone/calcareous sandstone unit, below the high-gamma mudstone of the Upper Bowland Shales. In the absence of the upper marker, particularly in the eastern wells, the formation top is picked at the base of the high-gamma mudstone of the Upper Bowland Shales.

Age

Palynomorphs from Cleveland Group D in wells 41/14- 1, 41/24a- 2, 43/17- 2, 43/21- 2 and Kirby Misperton 1 indicate a wide age interval from Brigantian to Arnsbergian.

Correlation with onshore UK

The limestone or calcareous sandstone at the top of the unit is known locally onshore as the Harrogate Roadstone (Andrews, 2013).

3.5.5 Upper Bowland Shales

Name

The term Upper Bowland Shales is used informally in the Cleveland Basin for lower Namurian, basinal, black mudstones and silty mudstones with high gamma values.

Lithology

The Upper Bowland Shales are characterised by at least one interval of a very high gamma values (representing black shales), in an otherwise thick, homogeneous sequence of mudstones with a sparse interbeds of siltstone, sandstone and dolomitic limestone. The thickness of the unit varies from 17 m in well 41/15- 1 to 136 m in Kirby Misperton 1.

Lower boundary

The base of the Upper Bowland Shales is taken above the top of the first limestone or calcareous sandstone beneath the high-gamma mudstone.

Upper boundary

The top of the Upper Bowland Shales is picked at the base of the lowermost sandstone unit in Cleveland Group E.

Age

The Upper Bowland Shales are late Brigantian and Pendleian in age, proved palynologically in wells 41/14- 1, 41/24a- 2, 43/17- 2 and Kirby Misperton 1.

Correlation with onshore UK

The Upper Bowland Shales are equivalent to the upper part of the Bowland Shale Formation in the Craven Basin. The high-gamma character is seen in the Bowland – Hodder unit of Andrews (2013) and suggests that a link between the Cleveland and Craven Basins was established for the first time in the Pendleian.

3.5.6 Cleveland Group E

Lithology

Cleveland Group E is defined as a relatively continuous succession of siltstones to fine-grained sandstones, with sporadic thin sandstone and limestone beds that lies stratigraphically beneath the Millstone Grit Formation and above the underlying Upper Bowland Shales. The unit is 105 m thick in Kirby Misperton 1 but varies from 88 m in well 42/16- 1 to 663 m in well 43/21-2 and 1265 m in well 43/17- 2.

Lower boundary

The base is taken at the base of the most significant siltstone or sandy siltstone above the high-gamma mudstone of the Upper Bowland Shales.

Upper boundary

The top is taken below the base of the most significant sandstone body in the Millstone Grit Formation.

Age

The Cleveland Group E contains palynomorphs in wells 41/14- 1, 43/17- 2 and Kirby Misperton 1 that indicate a Pendleian to Alportian age and appears to be diachronous. Palynological zonations in Quadrant 41 and in Kirby Misperton 1 indicate it is Pendleian to Arnsbergian in age. whilst in Quadrant 43 it continues into the Alportian.

3.6 MILLSTONE GRIT FORMATION

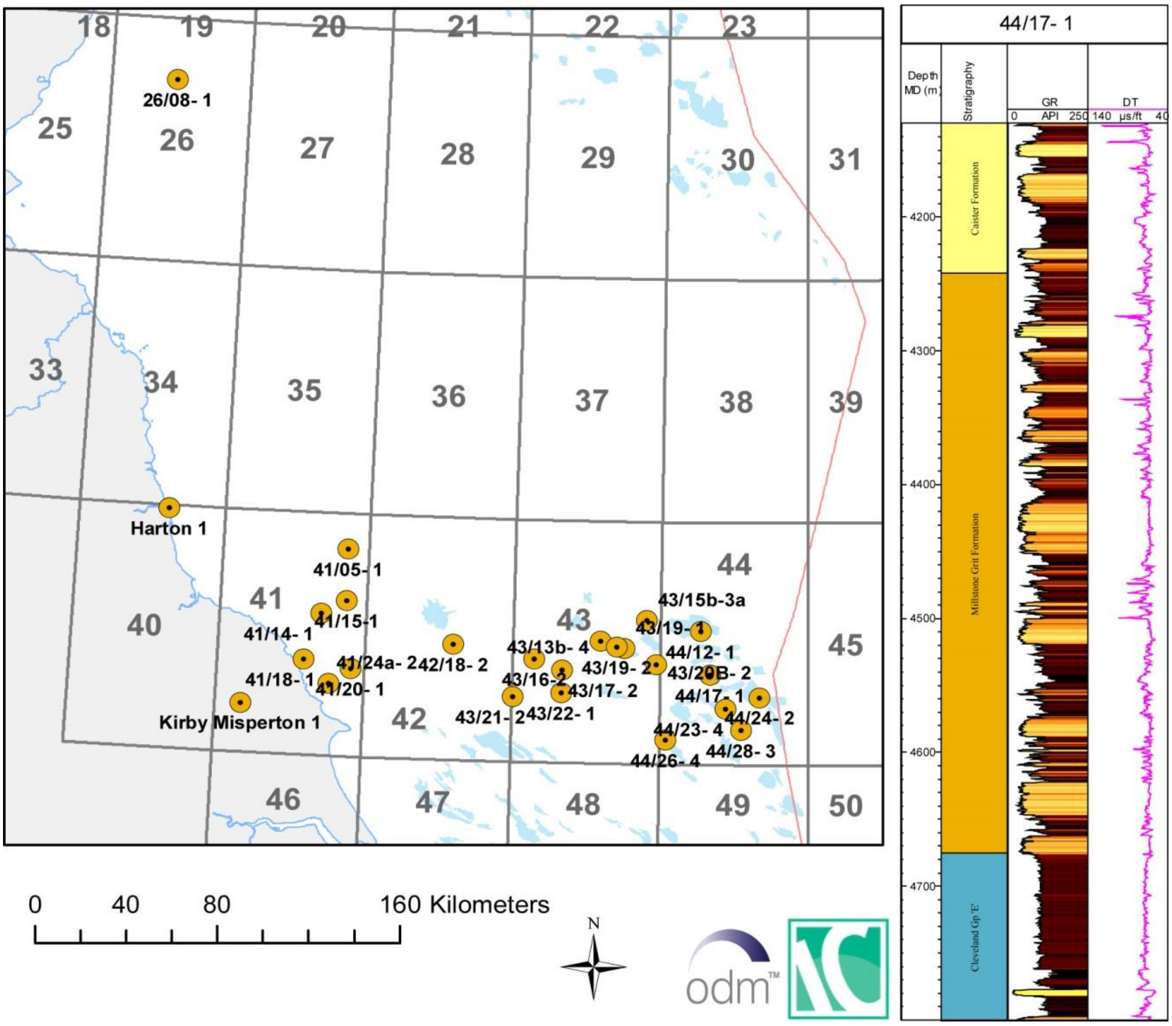

Figure 14: Map showing the distribution of wells proving the Millstone Grit Formation, and the key well profile that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

Historically, the term Millstone Grit was introduced by Whitehurst (1778) for the Carboniferous sandstones and shales in Derbyshire, whilst later, Phillips (1836) expanded the name to Millstone Grit Series to encompass all strata overlying the Bowland Shales, and overlain by Coal Measures (Cameron 1993a). More recently, BGS replaced the term with Millstone Grit Group (Aitkenhead et al. 1992). The presence of the Millstone Grit Group in the Alston Block and Northumberland Basin area has been reviewed recently by Waters et al. (2014). Cameron (1993a) proposed the term Millstone Grit Formation for the equivalent unit in the North Sea. Cameron's terminology is retailed herein as we have not divided the succession the offshore.

Geographical extent

The Millstone Grit Formation is widespread south of the Mid North Sea High to the London-Brabant Massif (Cameron, 1993a). It is recorded from wells in Quadrants 40, 41, 43, 44, and Cameron (1993a) referred to an outlier in the north of Quadrant 39. A 126 m thick sandstone unit with a blocky gamma-ray trace in well 26/08- 1 is tentatively correlated with the Midland Valley Passage Formation.

Lithology

The Millstone Grit Formation comprises cycles of sandstone, interbedded mudstone and siltstone, thin marine bands and sporadic thin coals. The sandstone is typically coarse and very coarse grained with some units containing common floating quartz pebbles. It lacks the upward coarsening cycles with limestones of the Yoredale Formation. The Millstone Grit Formation has been interpreted as a sequence of prograding fluvial and turbidite-fronted delta sequences accumulating in basinal areas (Collinson, 1988). It is at least 930 m thick across the study area.

Key Well

The conformable top and basal contacts of the Millstone Grit Formation have been observed in wells 44/17- 1, where it overlies Cleveland Group E, and is overlain by the Caister Formation. In Harton 1, the formation overlies the Yoredale Formation and is overlain by the Pennine Lower Coal Measures Formation.

Lower boundary

The base of the Millstone Grit Formation has been picked at the base of the lowermost significant sandstone unit where it rests on basinal mudstone of the Cleveland Group or on limestone-sandstone-mudstone cycles of the Yoredale Formation.

Upper boundary

The top of the Millstone Grit Formation is taken at the base of the lowest cluster of coal seams in the overlying Coal Measures (Caister Coal Formation). However, in most wells, the Millstone Grit is overlain unconformably by Permian strata.

Age

The Millstone Grit Formation is Pendleian to Yeadonian in age. However, the base of the formation is diachronous. In the Craven Basin onshore the lowest Millstone Grit units are Pendleian, whereas in Northumberland the lowest unit is Kinderscoutian (Waters et al. 2014).

Correlation with onshore UK

The Millstone Grit Formation is equivalent to its onshore namesake. In the Midland Valley of Scotland rocks of this age and facies form the Passage Formation.

3.7 CONYBEARE (COAL MEASURES) GROUP

The rocks that onshore comprise the Coal Measures Group were included as the lower part of the Conybeare Group in the North Sea by Cameron (1993a).The Coal Measure facies of that group was subdivided by Besly (2005), into the Caister Formation at the base, overlain successively by the Westoe and Cleaver Formations (Figure 2). The succession has been studied extensively across the Southern North Sea gas fields (e.g. Cole et al. 2005 and references therein) and the account here is brief.

3.7.1 Caister Formation

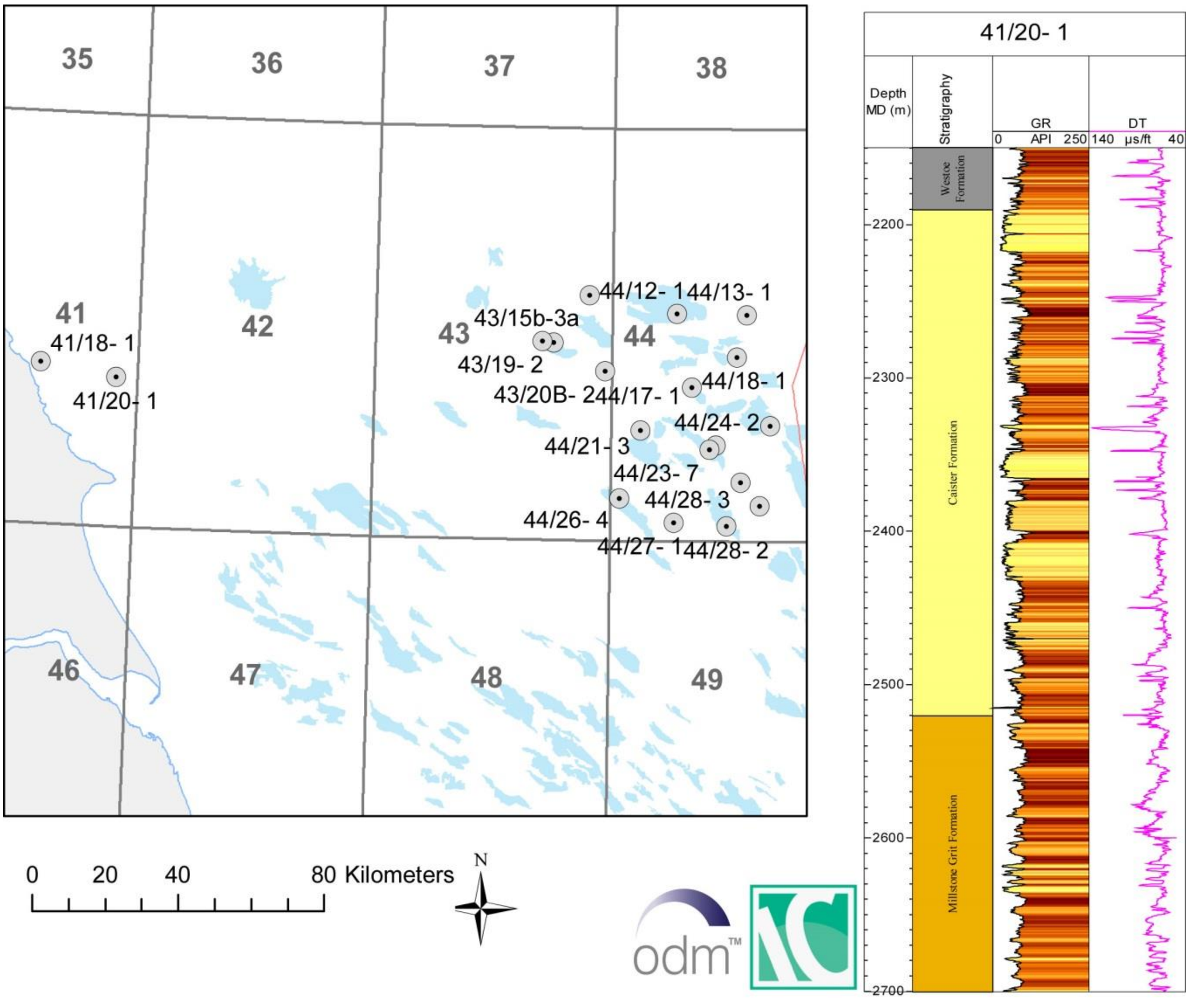

Figure 15 Map showing the distribution of studied wells where the Caister Formation has been proved, and the key well profile that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Caister Formation was introduced as the Caister Coal Formation by Cameron (1993a) for the basal division of the Conybeare Group in the Southern North Sea. The term "Coal" was omitted from the name by Besly (2005), as coal is not the dominant lithology of this unit. The unit includes the reservoir sandstones of the Caister and Murdoch Fields (Cameron 1993a).

Geographical extent

The Caister Formation has been proved in wells in Quadrants 41, 43 and 44. Its distribution and preservation below the base-Permian unconformity is controlled by Variscan folding and subsequent erosion (Cameron, 1993a).

Lithology

The Caister Formation succession is sandstone dominated, and interbedded with mudstone, siltstone and coal seams. The coals seams are up to 5 m thick, and constitute up to 5% of the formation (Cameron, 1993a). Major channel sandstone bodies are locally up to 50 m thick (Cowan, 1989). The Subcrenatum Marine Band is reported from the base of the formation in Quadrant 43 (Waters et al. 2011).

Key Wells

The conformable top and basal contacts of the Caister Formation have been proved in wells 41/18- 1, 41/20- 1 and 44/28- 3. All of these wells show a basal contact on the Millstone Grit Formation.

Lower boundary

The lower boundary is defined at the base of the lowest cluster of coal seams marked by low-velocity spike on sonic logs overlying the Millstone Grit Formation (Cameron, 1993a). The lower boundary can be defined on palynological evidence within the top of the FR Zone, below the Subcrenatum marine band (P. Osterloff, pers. comm.).

Upper boundary

The Caister Formation is overlain by the Westoe Formation, with the transitional boundary taken at the change from sandstone-rich, to siltstone-rich coal bearing strata. However, in many wells in the Southern North Sea, the Caister Formation is overlain unconformably by the Ketch Formation or by Permian strata (Cameron, 1993a).

Age

The Caister Formation is the oldest unit in the Conybeare Group. Most palynomorph determinations are indicative of a Langsettian to earliest Duckmantian age (McLean et al. 2005). The lower part of the formation in wells 44/28- 3 and 41/18- 1 has yielded palynomorphs of latest Namurian age (Yeadonian).

Correlation with onshore UK

The unit is equivalent to the onshore Langsettian Pennine Lower Coal Measures Formation, the base of which is taken at the Subcrenatum marine band.

3.7.2 Westoe Formation

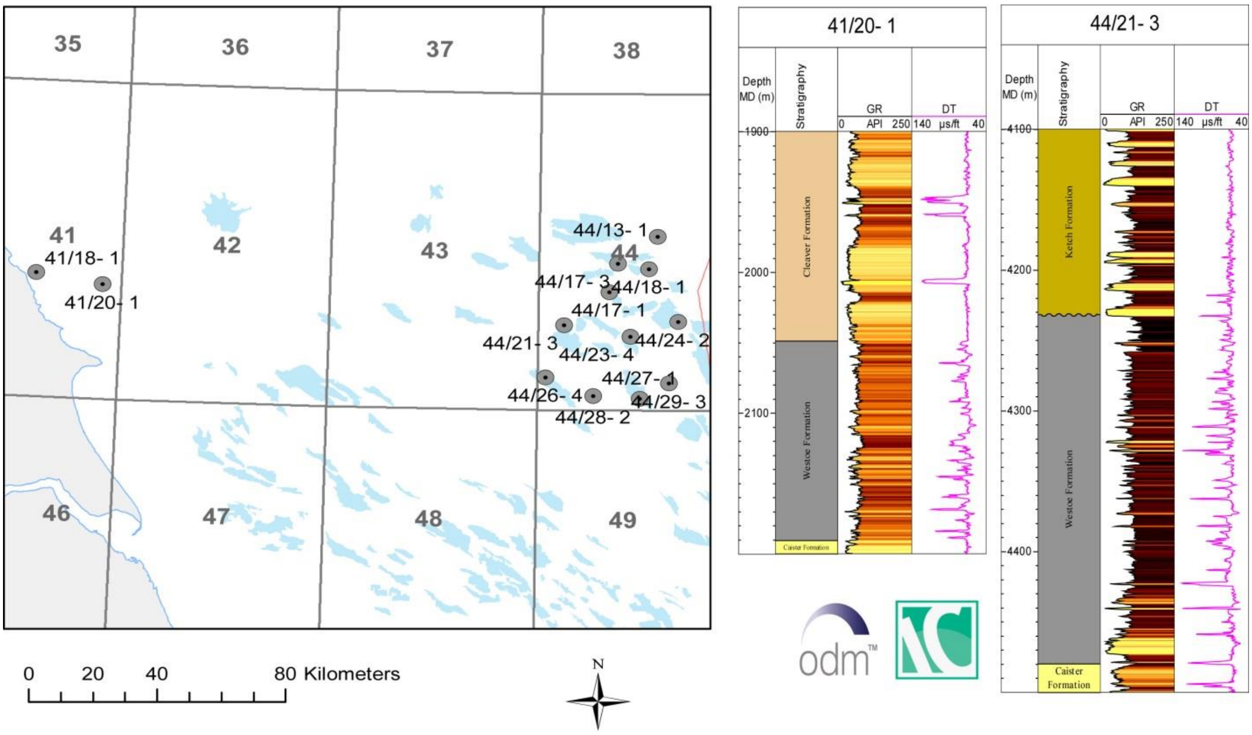

Figure 16 Map showing the distribution of the studied wells where the Westoe Formation has been proved, and the key well profiles that illustrate the principal variations in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Westoe Formation was introduced as the Westoe Coal Formation by Cameron (1993a) for the grey mudstone- and siltstone-dominated unit of the coal-bearing succession in the Southern North Sea. the term “Coal” was omitted from the name by Besly (2005) as coal is not the dominant lithology of this unit.

Geographical extent

The Westoe Formation has been proved in wells in Quadrants 41 and 44. Its distribution and preservation below the base-Permian unconformity is controlled by the Variscan folding (Cameron, 1993a).

Lithology

The dominant lithologies within the Westoe Formation are grey mudstone and siltstone with varying small proportions of seatearths, coal seams, and sandstone beds (Cameron, 1993a). Coal seams are common in all wells studied and can be up to 5 m thick. Cycles are less than 20 m thick and typically coarsen upward.

Key Wells

The conformable top and basal contacts of the Westoe Formation have been observed in wells 41/20-1 and 44/27-1. In some areas the Westoe Formation is overlain unconformably by the Ketch Formation as illustrated in well 44/21- 3.

Lower boundary

The Westoe Formation overlies the Caister Formation. The boundary is marked by the change from sandstone-rich Caister Formation, to siltstone-rich coal measures facies. The boundary is defined at the base of mudstone above the highest sandstone bed in the Caister Formation (Cameron, 1993a).

Upper boundary

The Westoe Formation is conformably overlain by the Cleaver Formation. The upper boundary of the Westoe Formation is marked by an increase in sand units in the succession. The top of the Westoe Formation is taken beneath the base of the first prominent sand body.

Age

The Westoe Formation is Duckmantian in age (McLean et al. 2005).

Correlation with onshore UK

The Westoe Formation is thought to be partly equivalent to the Pennine Middle Coal Measures Formation of England and Wales (Cameron, 1993a).

3.7.3 Cleaver Formation

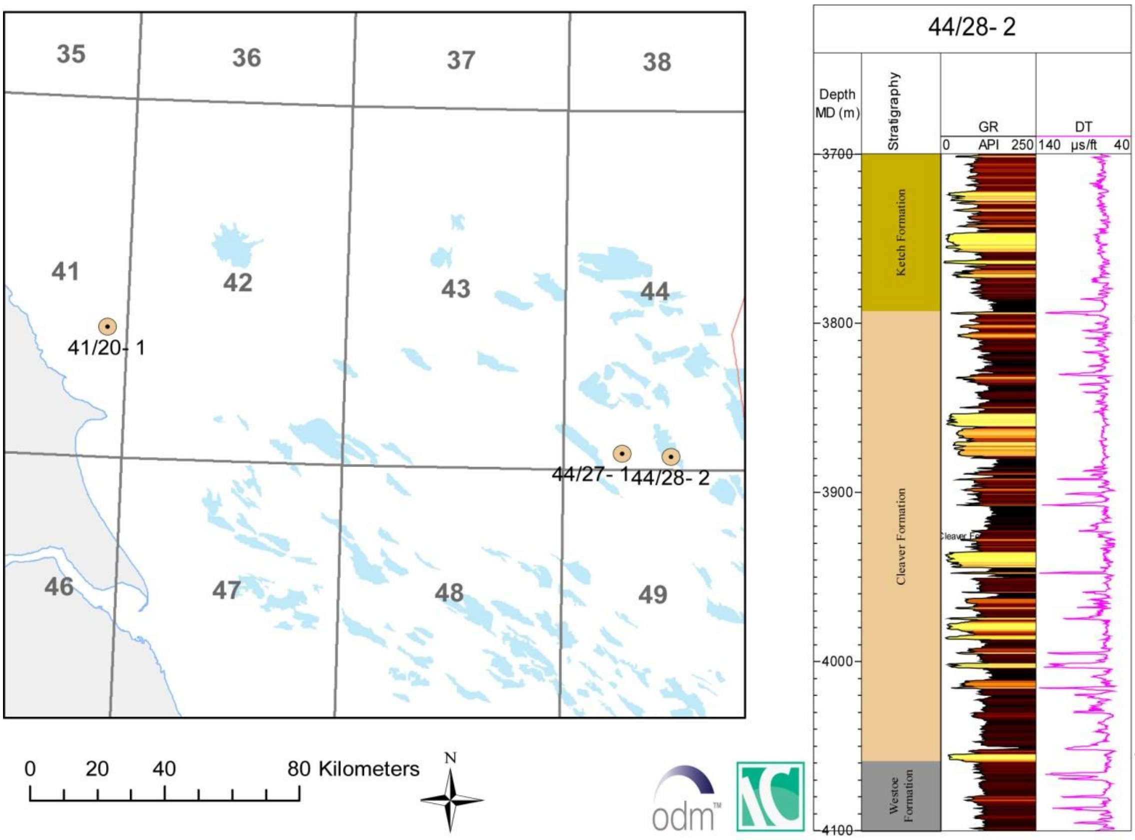

Figure 17 Map showing the distribution of studied wells where the Cleaver Formation has been proved, and the key well profile that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Cleaver Formation was introduced by Besly (2005) to distinguish an upper sand-rich, coal-bearing succession within the Schooner Formation of Cameron (1993a). The Cleaver Formation is included in the Conybeare Group.

Geographical extent

The Cleaver Formation is only present where it has not been eroded beneath the onlapping Ketch Formation. It has been identified in wells in Quadrants 41 and 44.

Lithology

The dominant lithologies within the Cleaver Formation are interbedded sandstone, mudstone, siltstone and coal seams. The sandstone units are up to 10 m thick and locally form viable reservoirs as seen in well 44/28- 2 (Besly, 2005). Substantial numbers of coal seams are present, particularly in the lower part of the formation.

Key Wells

The upper and lower contacts of the Cleaver Formation are observed in well 44/28- 2.

Lower boundary

The lower boundary of the Cleaver Formation is conformable with the Westoe Formation. The boundary is marked by an increase in sandstone in the coal measures succession. The base of the Cleaver Formation is taken at the base of the first prominent sand body.

Upper boundary

The Cleaver Formation is unconformably overlain by the Ketch Formation (Besly, 2005). The top of the Cleaver Formation is taken above the last significant coal.

Age

The Cleaver Formation is upper Duckmantian to middle Bolsovian (Waters et al. 2011).

Correlation with onshore UK

The Cleaver Formation is thought to be partly equivalent to the upper part of the Pennine Middle Coal Measures.

3.8 KETCH FORMATION

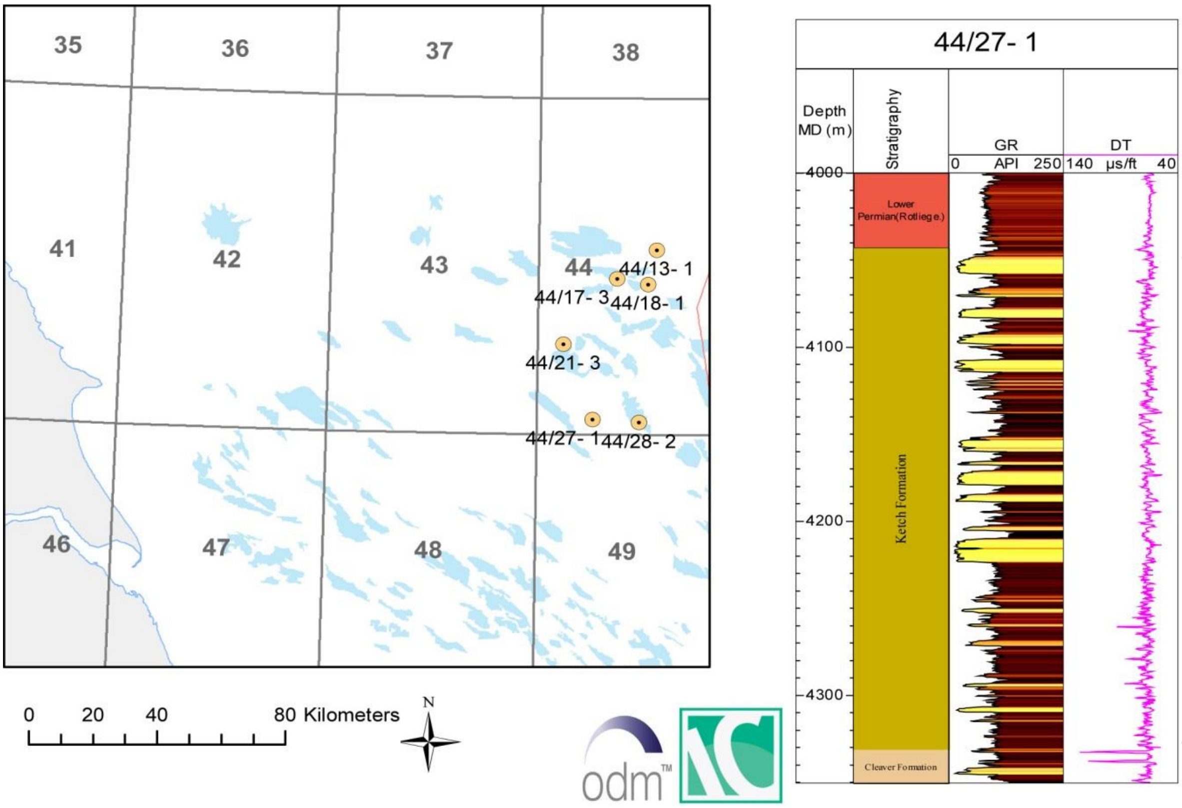

Figure 18 Map showing the distribution of the wells where the Ketch Formation has been proved, and the key well profile that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Ketch Formation was introduced as the Ketch Member of the Schooner Formation by Cameron (1993a). Subsequently it was shown that these rocks lie above an intra-Westphalian unconformity and that the Ketch Formation oversteps the Cleaver Formation northwards to overlie the Westoe Formation. The Ketch Formation (Besly, 2005), remains as part of the Conybeare Group.

Geographical extent

In this study, the Ketch Formation has only been identified in Quadrant 44, although Cameron, (1993a) described it from Quadrant 42.

Lithology

The Ketch Formation is a reddened succession containing sandstone beds up to 10 m thick interbedded with mudstone and siltstone. It also contains distinctive grey and ferruginous palaeosols and has a distinctive degraded kaolinite component in the clay mineralogy (Besly, 2005).

Key Wells

The upper and lower contacts of the Ketch Formation are observed in well 44/27- 1.

Lower boundary

The Ketch Formation unconformably overlies the Cleaver and Westoe formations (Besly, 2005). The base is taken above the top of the highest significant coal in the Cleaver or Westoe formation.

Upper boundary

In this are the Ketch Formation is overlain unconformably by Permian strata.

Age

The Ketch Formation is typically barren of palynomorphs, but has yielded taxa from the part of the SL Biozone of late Bolsovian age in well 44/21- 3 (Pearce et al. 2005). Palynomorphs assigned to the OT palynozone of Asturian age have been recorded in some Southern North Sea wells, from Ketch Formation equivalent strata (P. Osterloff, pers. comm.).

Correlation with onshore UK

The Ketch Formation is the offshore equivalent to the Keele Formation (Warwickshire Group) of central England Cameron (1993a).

3.9 UPPER CARBONIFEROUS TO LOWER PERMIAN STRATA OF THE FLORA FIELD

Upper Carboniferous to Lower Permian strata have been proved in wells in the Flora Field located off the Grensen Nose in Quadrants 31 and 39. The succession has been described by Martin et al. (2002) and Bruce and Stemmerik (2003). They recognised two sandstone dominated units, the Lower and Upper Flora sandstones, overlain by a mudstone–sandstone unit, referred to as the Grensen Formation. Basaltic volcanic rocks separate the Lower from the Upper Flora sandstone in some of the wells and overlie the Grensen Formation in others. Seismic data indicate that the area is structurally complex, though no significant faults that affect the stratigraphy have been interpreted by Martin et al. (2002). Furthermore, the seismic data suggest that there is also stratigraphic complexity. The correlation proposed by Martin et al. (2002) is shown in Figure 20.

3.9.1 Lower and Upper Flora sandstones

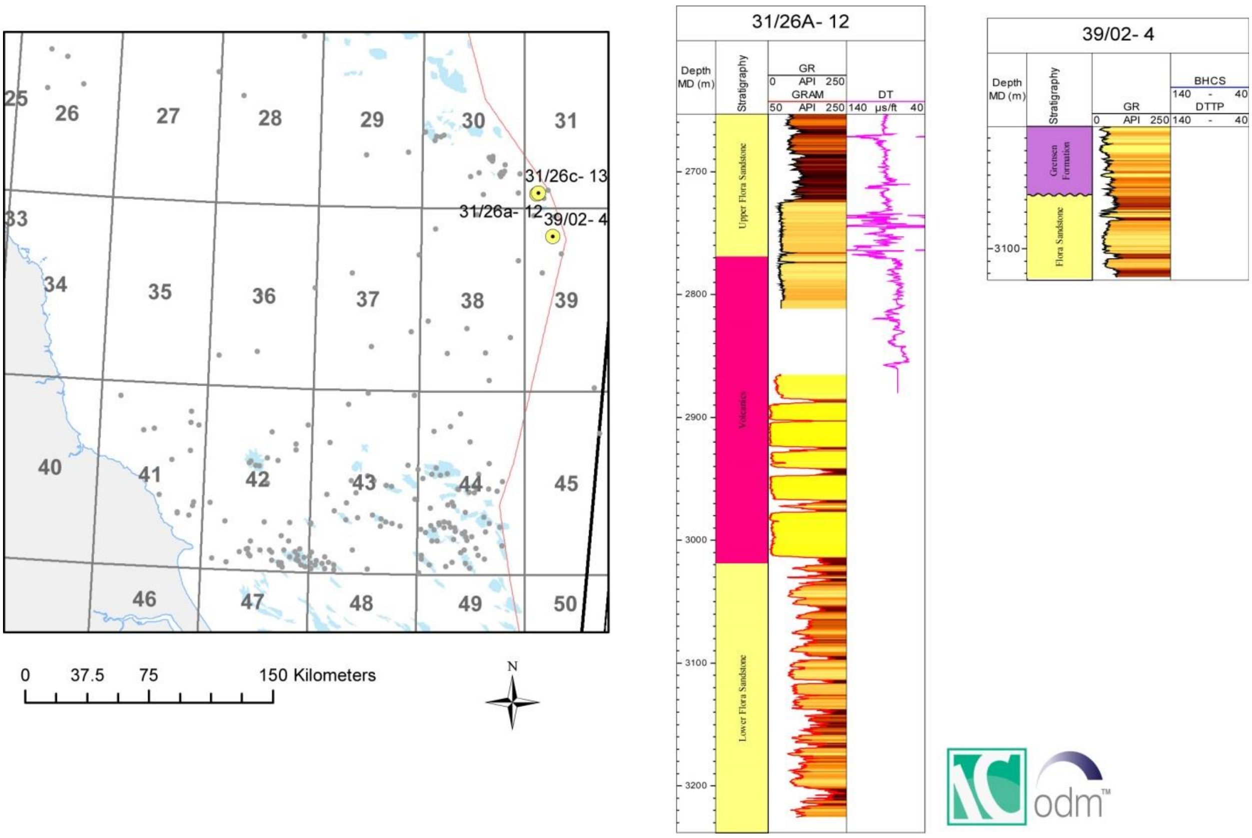

Figure 19 Map showing the distribution of wells where the Flora Sandstones have been interpreted, and the key well profile that illustrates the principal variations in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The terms Upper and Lower Flora Sandstone were proposed by Martin et al. (2002) for sandstone-rich units separated by volcanic rocks in well 31/26a-12, the only well where both sedimentary units are seen.

The Lower Flora Sandstone is proved in well 31/26a- 12 and has a characteristic spiky gamma-ray signature with blocky sandstone intervals interbedded with generally thin mudstone units, and quite distinct from the cyclicity seen in the Upper Flora Sandstone (Martin et al., 2002). The sandstone units in the Lower Flora Sandstone have sharp bases, but the units neither fine nor coarsen upward. The base of the formation has not been proved.

The sedimentology of the Upper Flora Sandstone has been described in detail using wireline log data and cored sections from well 31/26c-13 (Martin et al. 2002). The succession in that well is divided in a basal braided/anastomosing channel sandstone unit, overlain by braided sand-dominated channel deposits and capped by a braided gravel and sand channel unit. Inflections in the wireline log curves from wells 31/26- 1, 31/26c- 13 and 31/26a-12 can be correlated clearly with the succession displaying some cyclicity. The thin succession of sandstone and mudstone at the base of well 39/02- 4, is inferred also to belong to the Upper Flora Sandstone. The sandstone-dominated succession is thought to have been deposited in well-drained or dry continental environments (Martin et al., 2002).

Palynomorphs indicative of a Bolsovian to Asturian age have been reported from the Upper Flora Sandstone in well 31/26c- 13 and 39/02- 4, and from the Lower Flora Sandstone in well 31/26a- 12 by Martin et al. (2002), but we have been unable to assess the original report independently.

The Upper and Lower Flora sandstones were deposited contemporaneously with the Warwickshire Group onshore and the Ketch Formation in the Silverpit Basin, but direct correlation is not implied with the data currently available.

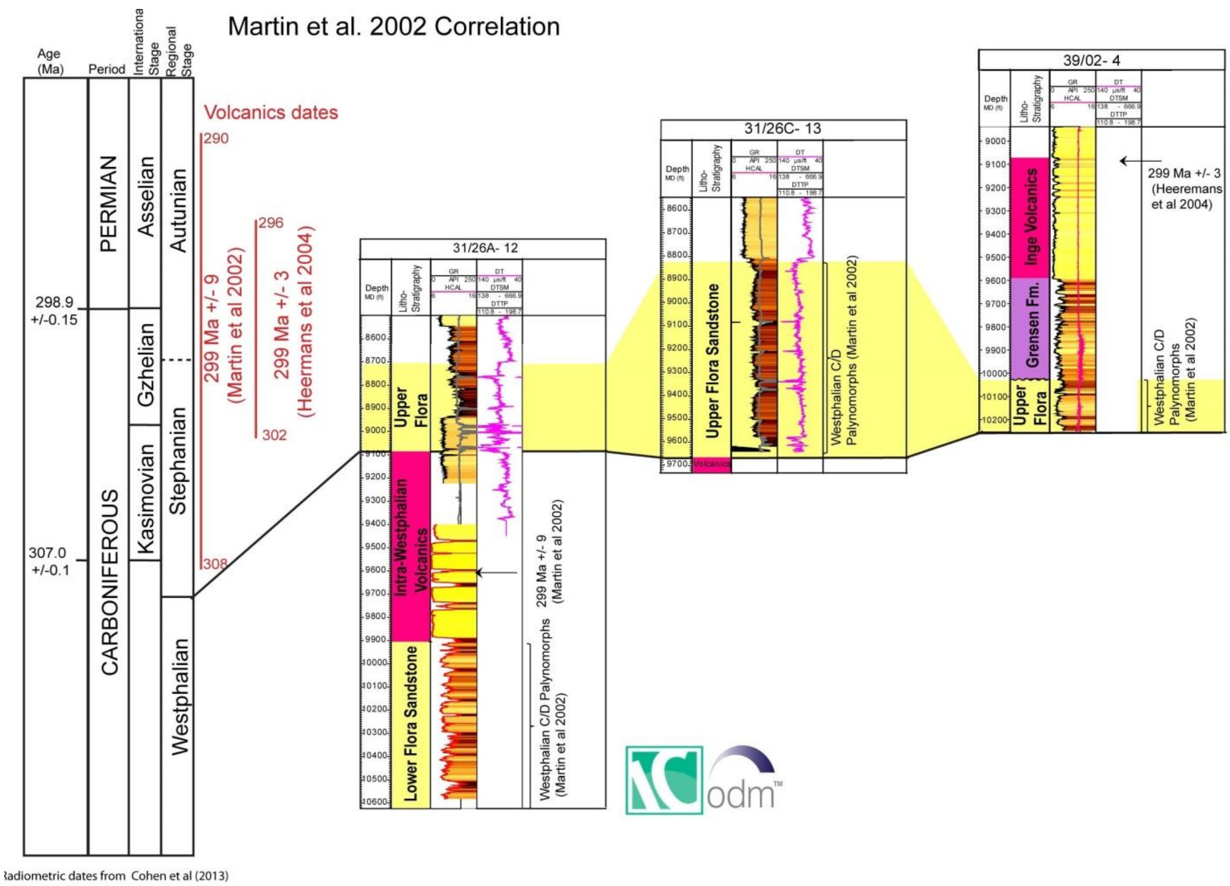

Figure 20 Correlation between the Upper Carboniferous to Lower Permian succession in the Flora Field, after Martin et al. (2002).

3.9.2 Grensen Formation

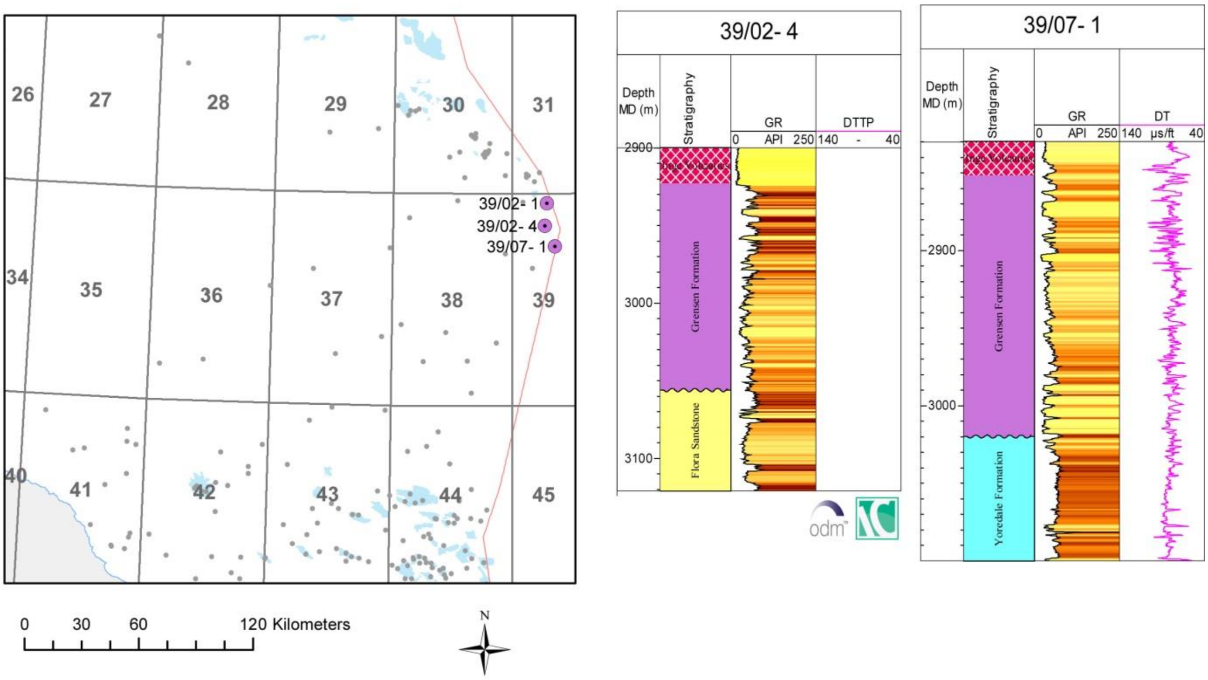

Figure 21: Map showing the location of wells where the Grensen Formation has been interpreted, and the key well profiles that illustrate the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Grensen Formation was recognised informally by Bruce and Stemmerik (2003).

Geographical extent and key wells

The Grensen Formation is interpreted to be present in wells 39/02- 1, 4 and 39/07- 1 in the southern part of the Flora Field. The formation unconformably overlies the Upper Flora Sandstone in well 39/02- 4 and the Yoredale Formation in wells 39/02- 1 and 39/07- 1. In all of the wells the Grensen Formation is overlain by volcanic rocks of the Inge Volcanic Formation (see below).

Lithology

The Grensen Formation is a succession of interbedded mudstone and sandstone, the latter in units up to 3 metres thick. It has been interpreted as being deposited in a fluvial or alluvial setting. The formation appears to thicken to the south and west. Bruce and Stemmerik (2003) have suggested that the heavy mineral assemblage has more affinity to Permian than to other Carboniferous sandstones.

Age

The Grensen Formation has proved to be barren of organic material (Bruce and Stemmerik, 2003). Heeremans et al. (2004) determined an Ar-Ar date of 299 ±3 Ma on the volcanic rocks above the Grensen Formation in well 39/02- 4, implying that the Grensen Formation has a late Carboniferous age.

3.9.3 Volcanic rocks

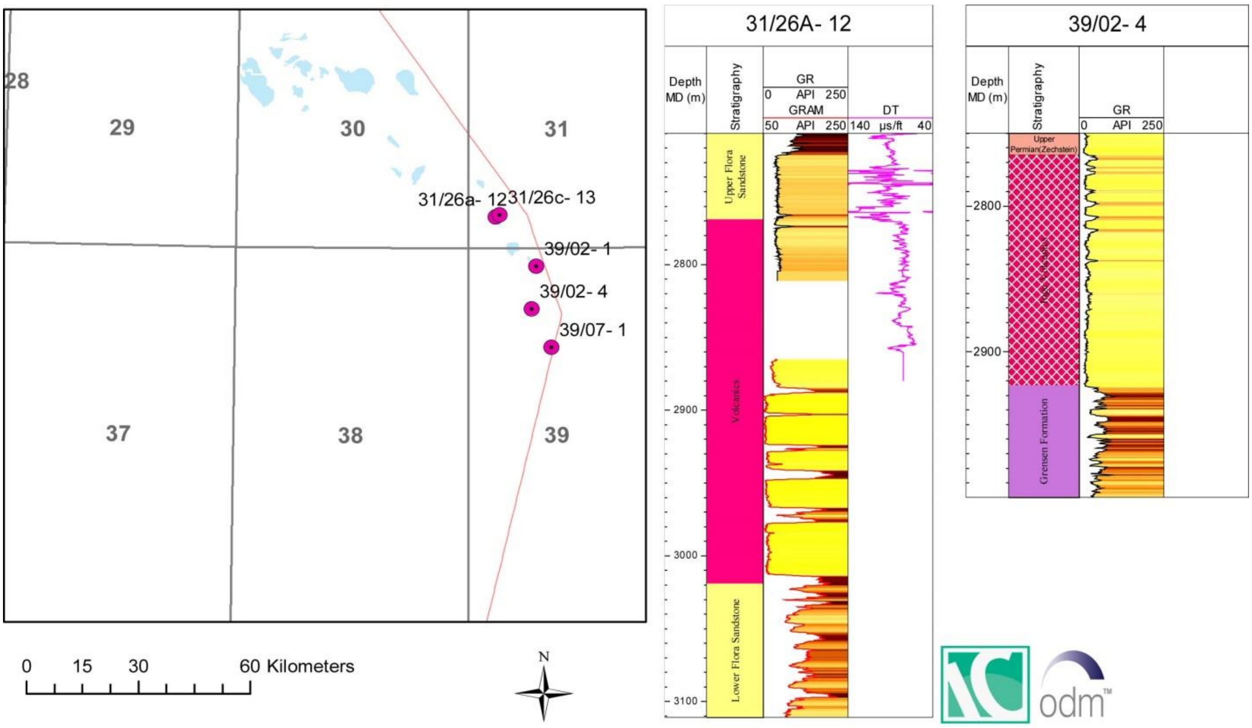

Figure 22 Map showing the distribution of wells where volcanic rocks have been interpreted, and the key well profile that illustrates the principal variations in wireline log signature (gamma and sonic logs) and lithology of the unit.

The Inge Volcanics Formation was introduced by Cameron (1993a) for volcanic rocks proved in wells 31/26a- 12, 31/26c- 13, 39/02- 1, 4, and 39/07- 1 in Quadrants 31 and 39. The volcanic rocks comprise basalt, volcaniclastic rocks and interbedded claystone and sandstone and have distinctive wireline log responses (Cameron, 1993a; Heeremans et al., 2004).

Martin et al. (2002) recognised that there are two volcanic units, the first separating the Upper and Lower Flora sandstones and the second overlying the Grensen Formation (Figures 22, 29). Martin et al. (2002) determined a whole rock K-Ar radiometric age of 299±9 Ma for the lower unit in well 31/26a-12. The substantial error means that this date is permissible with the Westphalian biostratigraphical determinations on the enveloping Flora sandstones. Interpretation of the seismic data by Martin et al. (2002) shows that in the Quadrant 39 wells there is only a single volcanic unit, referred by them to the “upper volcanic unit (Inge Volcanics)”. In this area the lower volcanic unit is apparently not preserved. Later, Heeremans et al. (2004) obtained a more precise Ar-Ar age of 299± 3 Ma for the upper volcanic unit proved in well 39/02- 4 and this unit is equated with the Inge Volcanics Formation. Thus, two volcanic events are represented in the Flora Field, an earlier, Westphalian event, and a later one near to the Carboniferous – Permian boundary.

The two volcanic units are considered to be associated with the widespread late Carboniferous – early Permian tholeiitic magmatism stretching from Scotland and Northumberland to the Oslo Graben (Heeremans et al., 2004; Stephenson et al. 2003).

3.10 INTRUSIVE IGNEOUS ROCKS

The Whin Sill Swarm was intruded into the Visean, Namurian and Westphalian rocks throughout much of northern England in earliest Permian times (Stone et al. 2010 and references therein). In the coastal region it was recorded within the Yoredale Formation in Seal Sands and Harton 1 wells and offshore in well 41/01- 1. Within Harton 1, there are three individual sheets with a combined thickness of around 90 m. One 16 m thick sheet was encountered within Seal Sands No. 1 well and a 27 m thick single sheet within well 41/01- 1. The Whin Sill has not been encountered in any other well examined during this study, suggesting the swarm terminates east from well 41/01- 1.

4 Correlation Panels

To illustrate the stratigraphic relationships and lithofacies variations of the Carboniferous and Devonian rocks of the Central North Sea and Mid North Sea High, nine correlation panels have been constructed across the area (Figure 1). The panels were also used to aid seismic interpretation. Portions where biostratigraphic constraints were available in wells are marked with a plus (+) symbol in the biostratigraphy column.

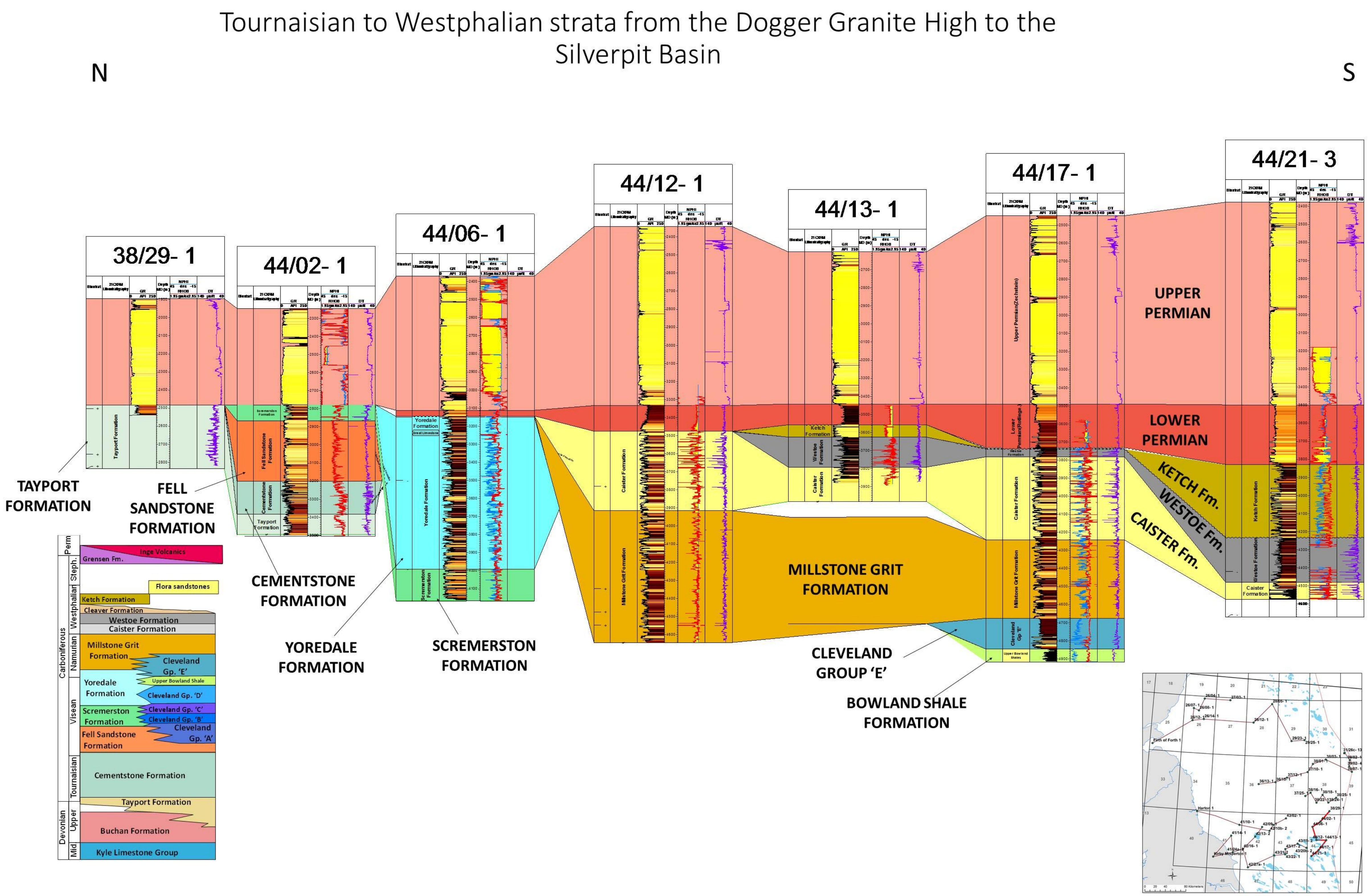

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Figure 23 North-South correlation panel from the Dogger Granite High in Quadrant 38 south into Quadrant 44 showing how Lower Carboniferous stratigraphy is related to Namurian and Westphalian stratigraphy in the Silverpit Basin. This panel shows the most southerly occurrence of the Tayport Formation in this study. It also shows a dramatic stratigraphic jump between the wells 44/06- 1 to 44/12- 1, due to faulting south of the Dogger Granite High.

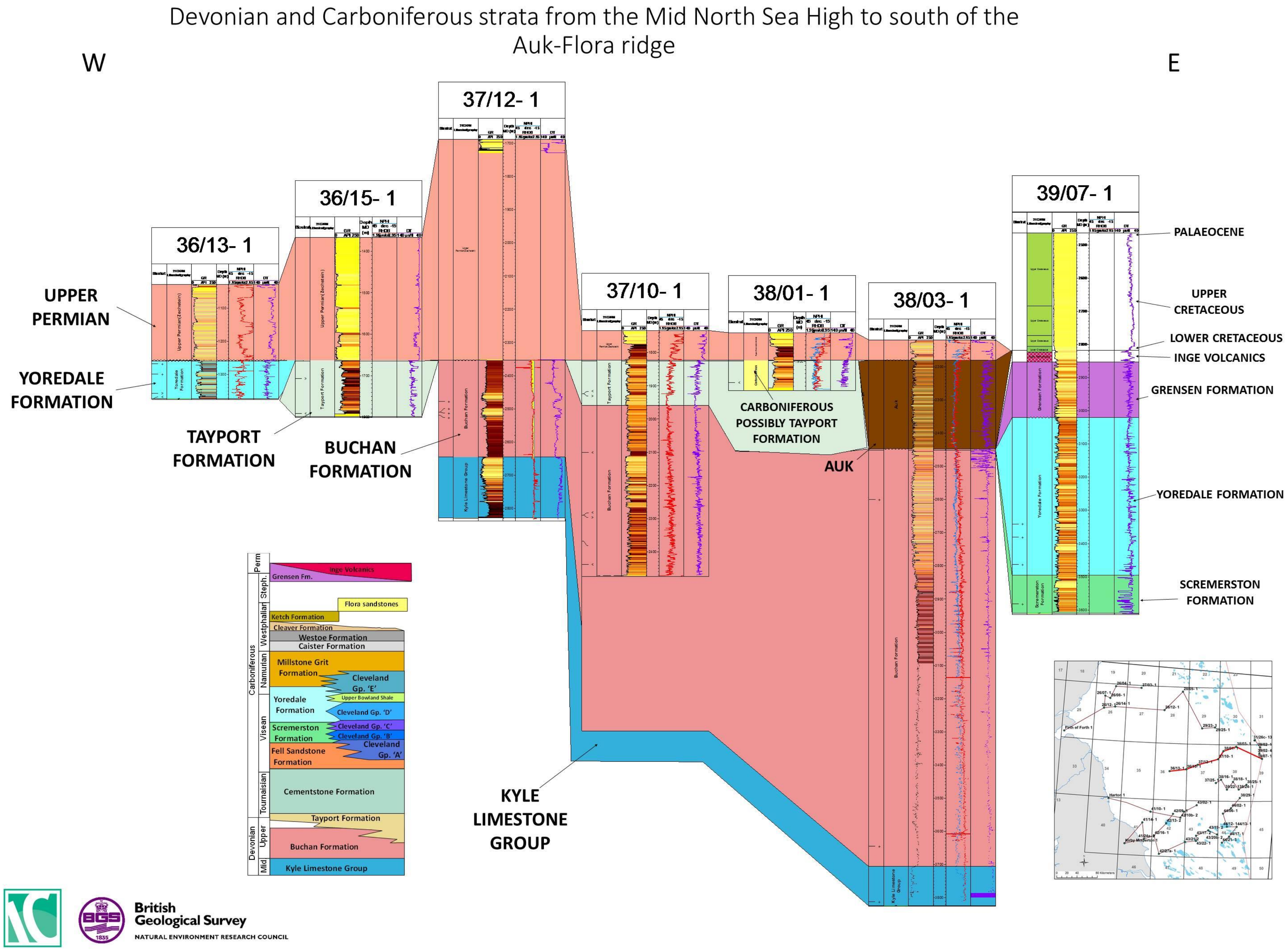

Figure 24 West-East correlation panel from the Mid North Sea High into the North Dogger Basin and on to the Auk-Flora ridge, showing wells proving the Kyle Group and Buchan Formation. The Tournaisian to Namurian Carboniferous strata in the North Dogger basin and in Quadrant 39 are also shown.

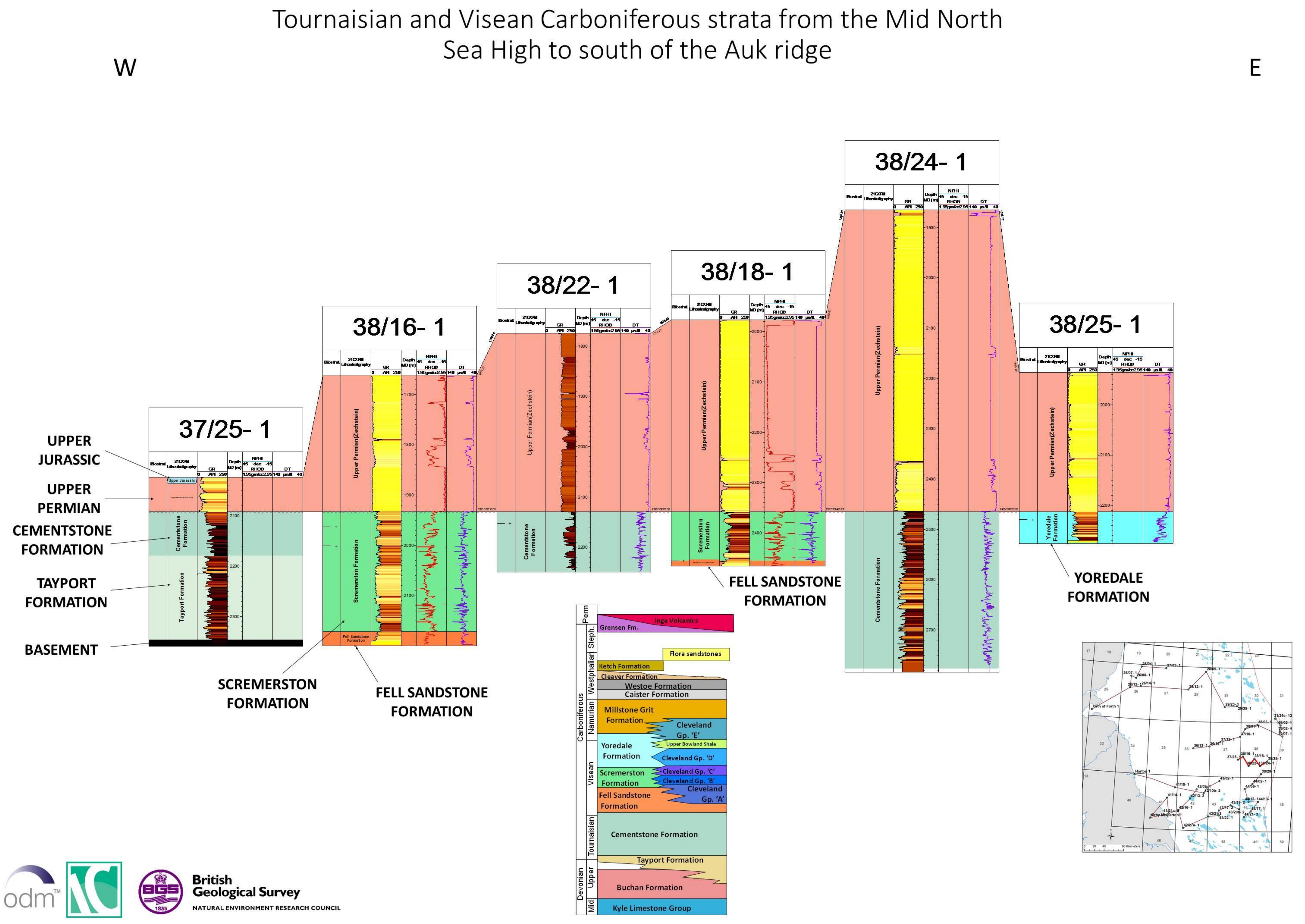

Figure 25 West-East correlation panel from the Mid North Sea High to south of the Auk Ridge highlighting the variability in Tournaisian and Visean strata east of the Dogger Granite High and into the North Dogger Basin in Quadrant 38.

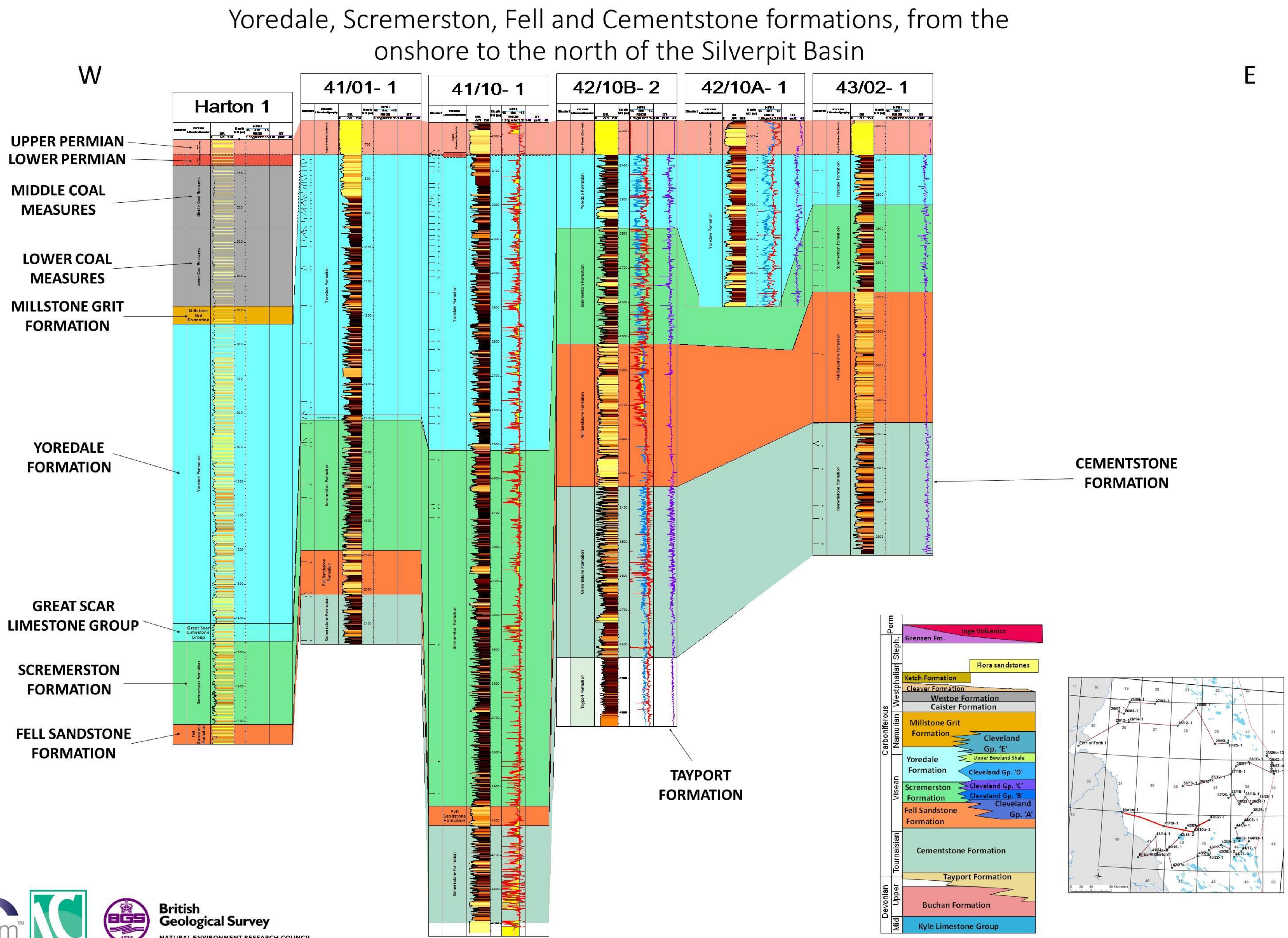

Figure 26: A broadly west to east profile across the Yoredale, Scremerston, Fell and Cementstone formations, from the onshore Harton 1 well in the west (Alston Block) to 43/02-1 (north of the Silverpit Basin) to the east. The character of each formation varies little across the panel, with the Yoredale Formation exhibiting typical upward coarsening sequences with limestones. The Whitby Sandstone Member, identified by two distinct leaves of sandstone separated by a mudstone in the gamma log, is found in the lower part of the Yoredale Formation in 41/10- 1, 42/10b- 2 and 43/02- 1.

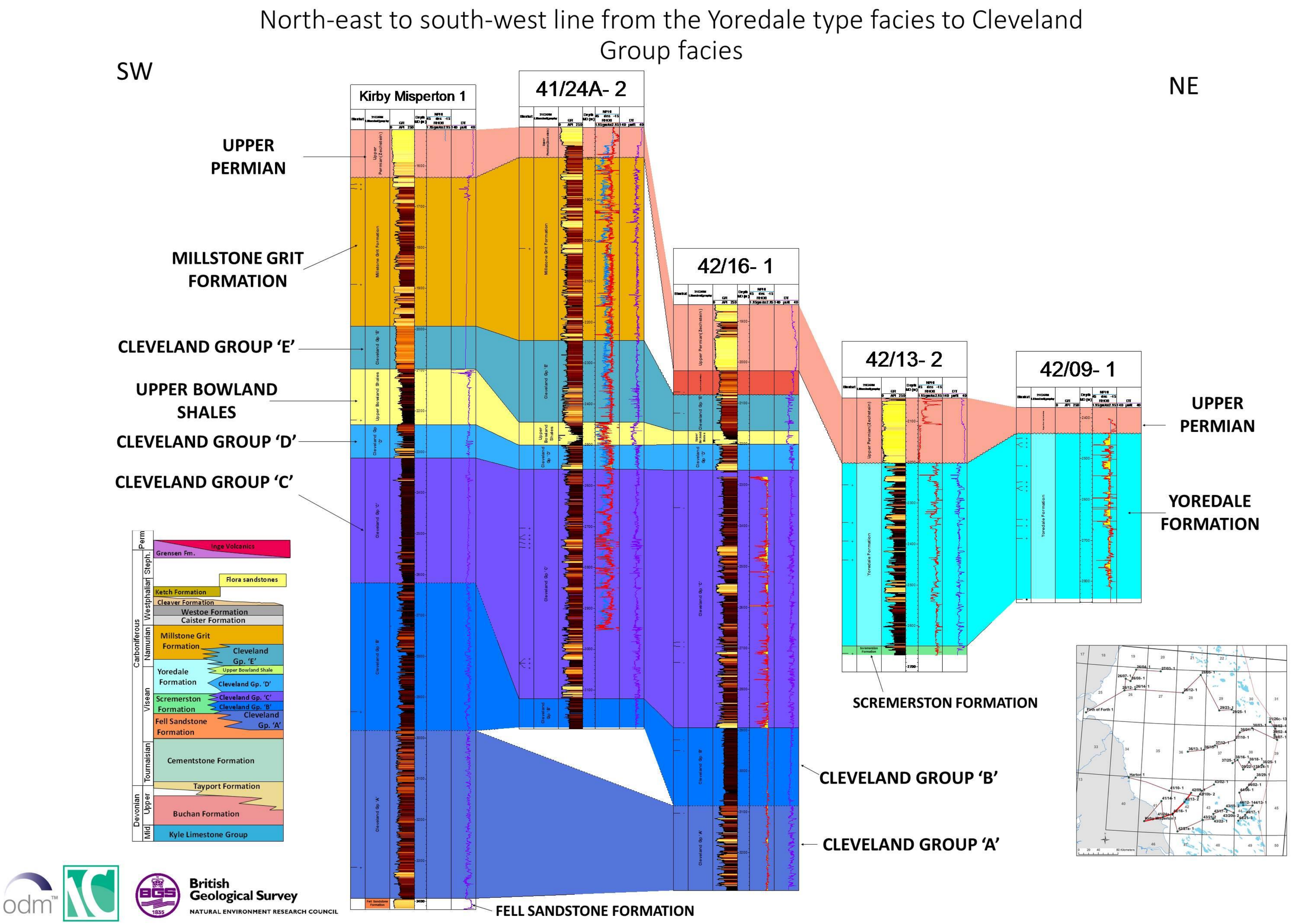

Figure 27: Comparison of Yoredale type facies from north of Quadrant 42 to Cleveland Group facies, in a line running from north-east to south-west, terminating in the onshore Kirby Misperton 1 well. The panel crosses the northern margin of the offshore Cleveland Basin, between deltaic upward coarsening Yoredale-type sequences and the time equivalent Cleveland Group mudstone and shale-dominated sequences.

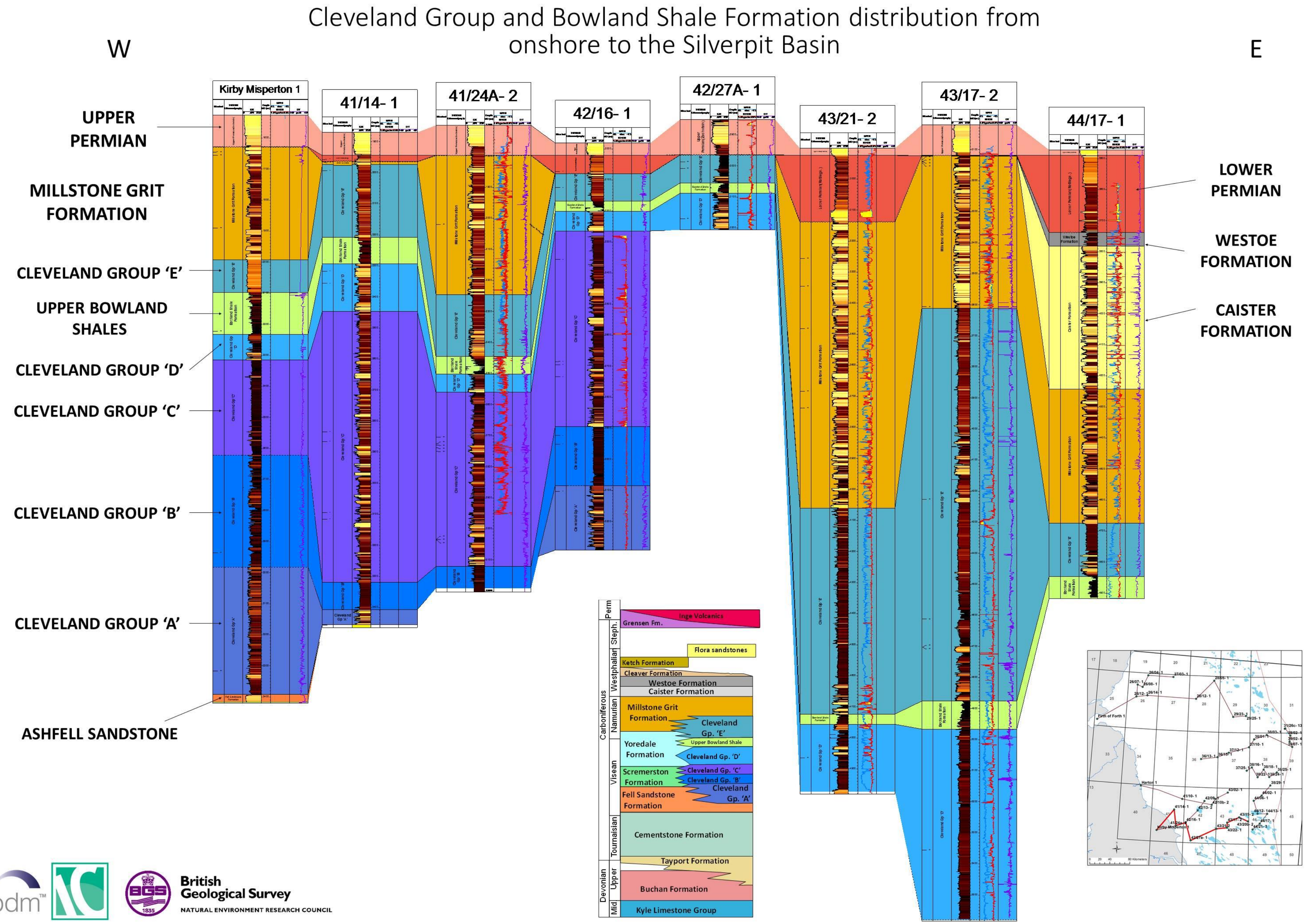

Figure 28 Cleveland Group and Bowland Shale Formation distribution, west to east across Quadrants 41, 42 and 43. The transition from the Cleveland Group 'E' and the Millstone Grit Formation is diachronous and both were being deposited in different parts of the basin from Arnsbergian to Alportian stages. The amount of sandstone in the Millstone Grit Formation is also variable across the Quadrants, and is typically more sandstone-rich in the east.

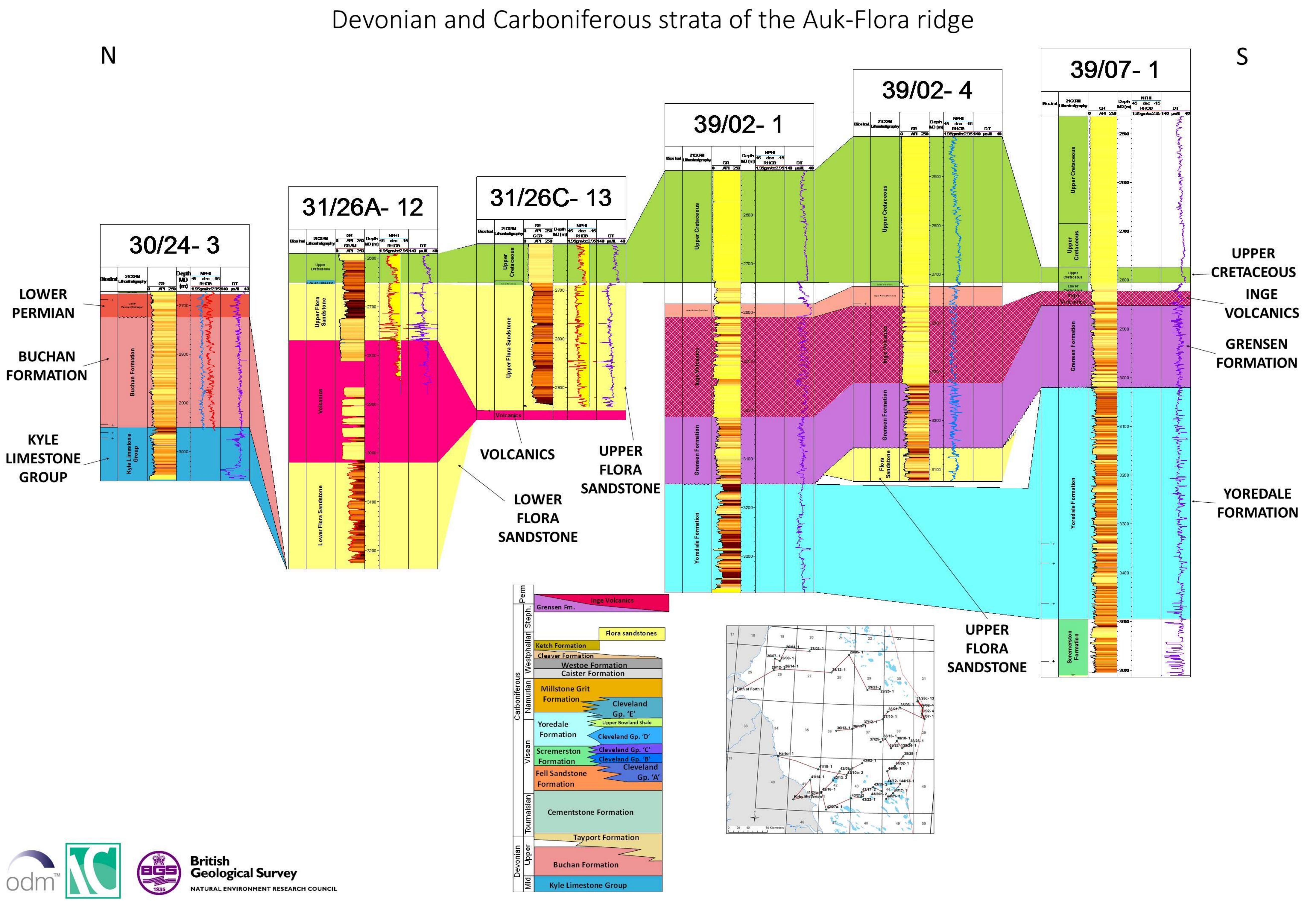

Figure 29 Devonian and Carboniferous strata of the Auk-Flora ridge from Quadrant 31 to 39,.

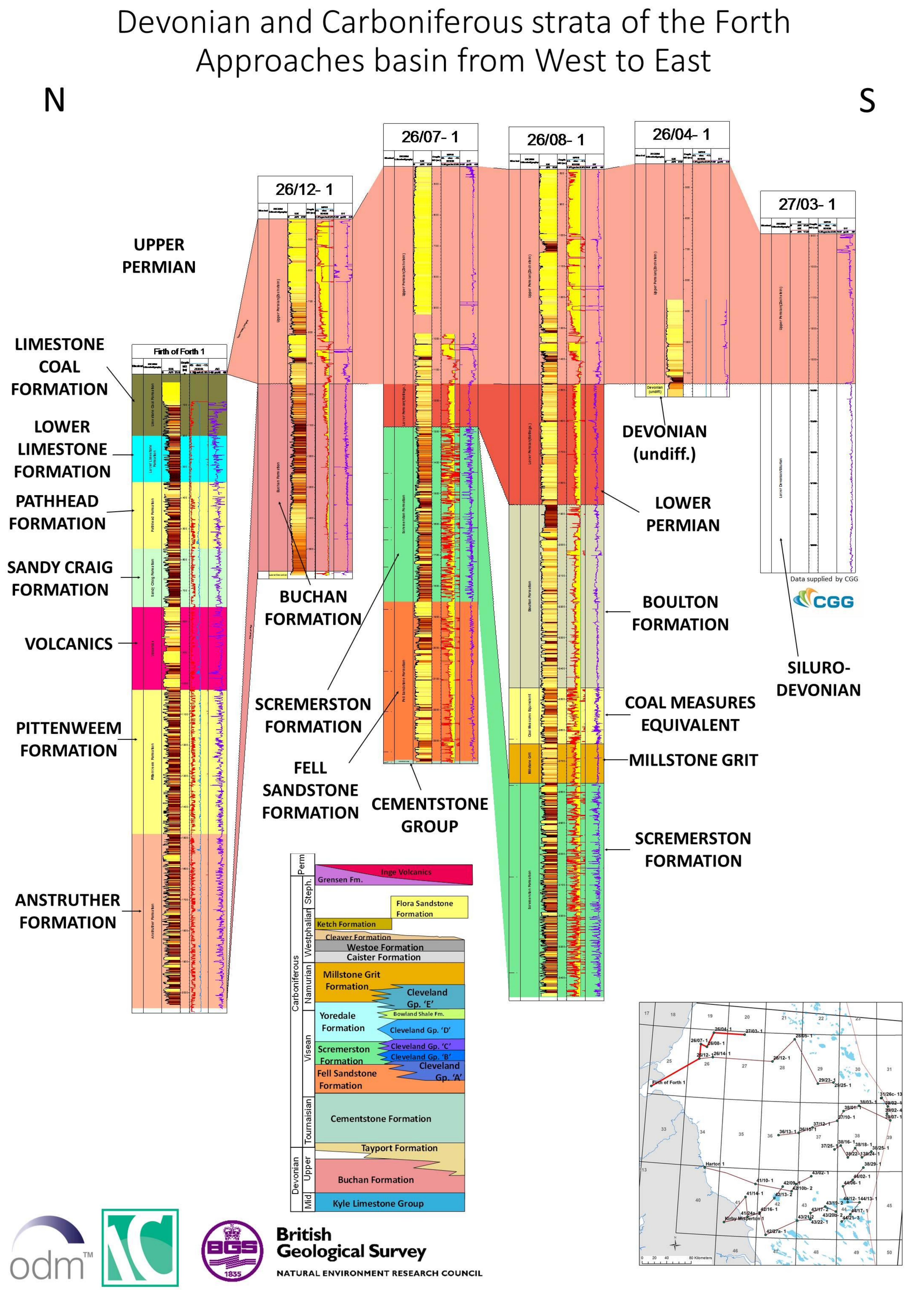

Figure 30 Devonian and Carboniferous strata of the Forth Approaches basin from West to East. Note that palynomorphs in the base of 26/07- 1 indicate the top Cementstone Formation and this matches with characteristic seismic reflectors just below the well TD.

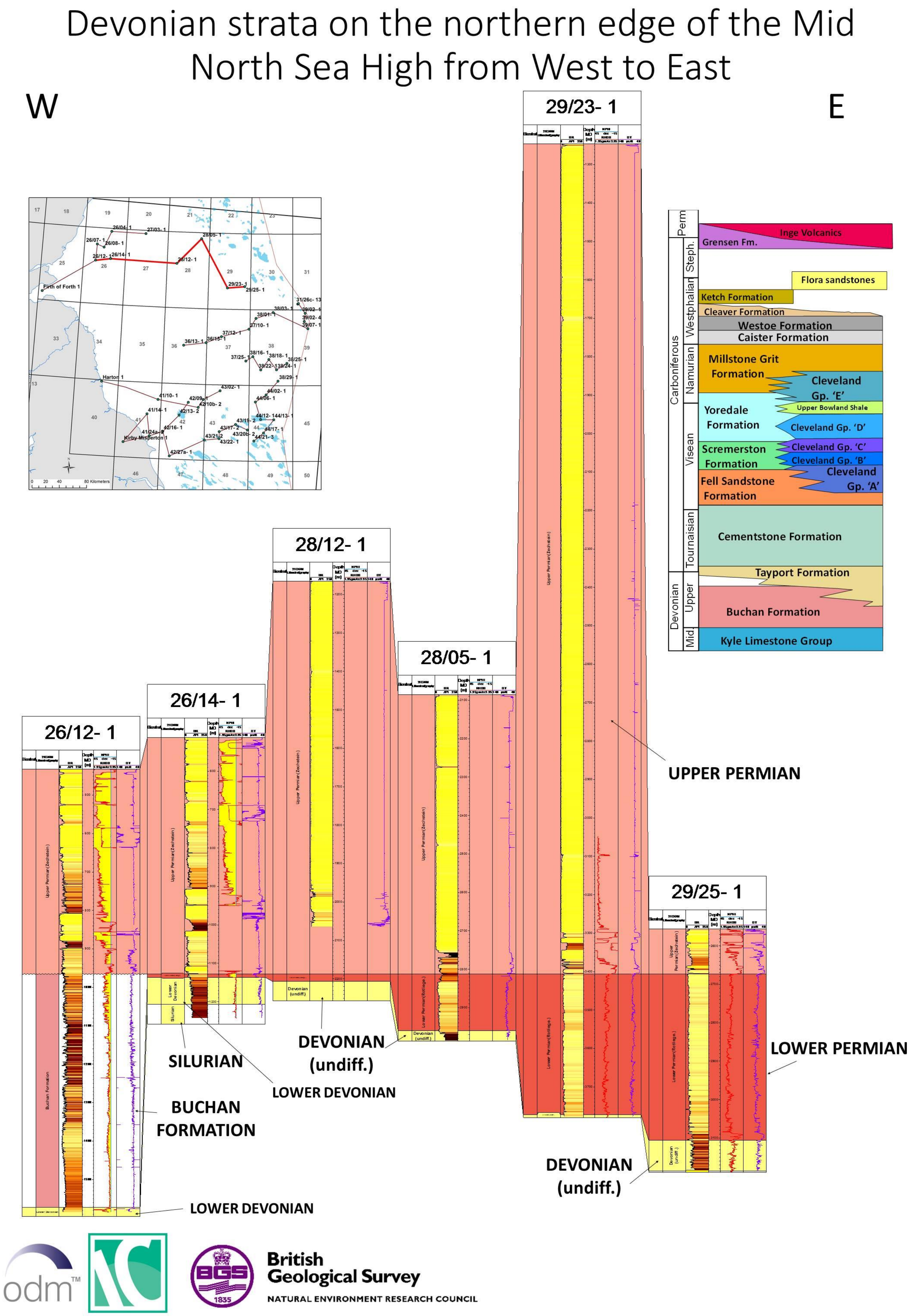

Figure 31 Devonian stratigraphy on the northern edge of the Mid North Sea High from West to East

5 Palaeogeography

Six time-slices are presented from the Mississippian and early Pennsylvanian. They 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 maps attempt to portray not only where the major lithofacies were deposited during the given time-slices, but also incorporates subcrop data to show where these rocks have been removed during late Carboniferous and Early Permian uplift and erosion. Thus, perhaps the most widespread Carboniferous rocks at subcrop across the Mid North Sea High are the Tournaisian formations.

Some general features of the geological evolution of the region are evident from these maps. Onshore in northern England, sediment accumulation through the Mississippian is controlled by the marked granite-cored blocks and basin structure which became established in Tournaisian times. The markedly thicker succession in the onshore Northumberland Basin relative to the blocks does not appear to be repeated offshore where thickening of sedimentary successions in the hanging wall of faults is nowhere proved as a typical syn-rift wedge of divergent reflectors. This onshore basin had little or no topographical expression (Brand 2011).

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

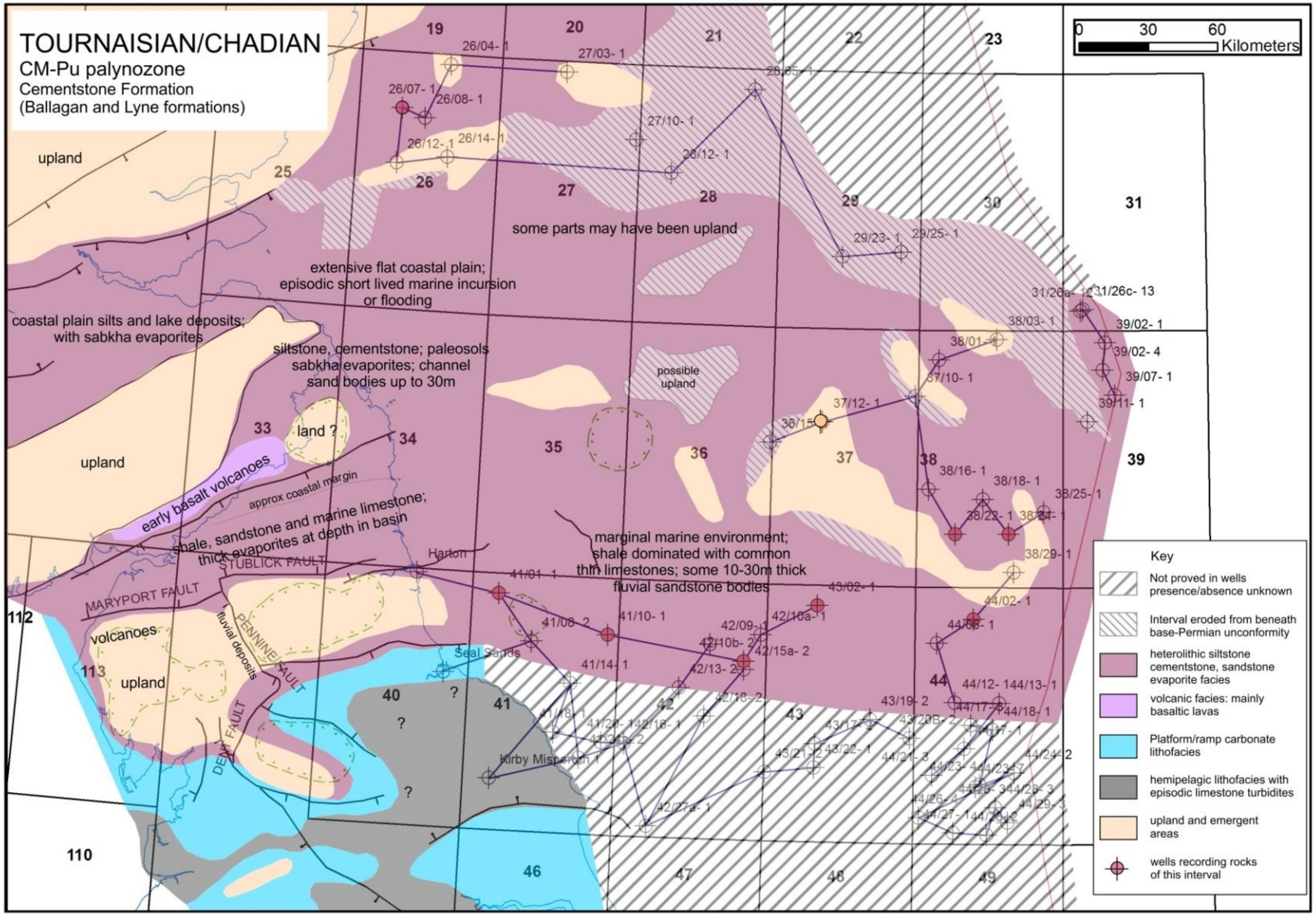

Figure 32 Tournaisian to Chadian palaeogeography (CM- early Pu palynozones)

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

Offshore: Cementstone Formation.

Onshore: Ballagan and Lyne formations

During this interval, coastal plain to marginal marine conditions were widespread across the region. In the Midland Valley of Scotland, Forth Approaches Basin and around Berwick upon Tweed, coastal-plain siltstones are interbedded with lacustrine siltstones and cementstones; the latter, typically in beds up to 1 m thick were probably deposited in saline lagoons (Anderton 1985; Scott 1986; Andrews et al. 1991). Abundant palaeosols testify to terrestrial conditions including the development of forests. Fluvial sandstone bodies make up about 30% of the succession in the northern parts of Quadrant 33, adjacent to the Southern Uplands, but are sporadic elsewhere. 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. Marine incursions in this area are typically cryptic. Thicker, probably marine, anhydrite deposits have been reported from the Northumberland Basin (Ward, 1998). The more marine character of the Northumberland Basin and of the succession in the wells in the northern sector of Quadrants 41-44 is also shown by the presence of limestones up to 10 m thick, containing a marine invertebrate fauna and representing more sustained marine conditions, typical of the Lyne Formation in Northumberland (formerly Lower Border Group, *sensu* Day, 1970).

Interpretation of the seismic data across Quadrants 34 to 38 suggests that the Cementstone Formation pinches out adjacent to ‘highs’ which may represent emergent, possibly upland areas, just as is seen onshore with the Southern Uplands, Cheviot, Lake District and Alston blocks. The emerging picture is of a ‘barrier island’ type of coastline, with restricted marine conditions to the south and coastal plain to the north.

Onshore, the Ballagan Formation mudstones have low TOC values and probably do not have significant source-rock potential (Monaghan, 2014). The channel sandbodies present are typically less than 20 m thick, but any substantial lateral continuity has not been proved.

5.2 ARUNDIAN (LATE PU – EARLY TS PALYNOZONES)

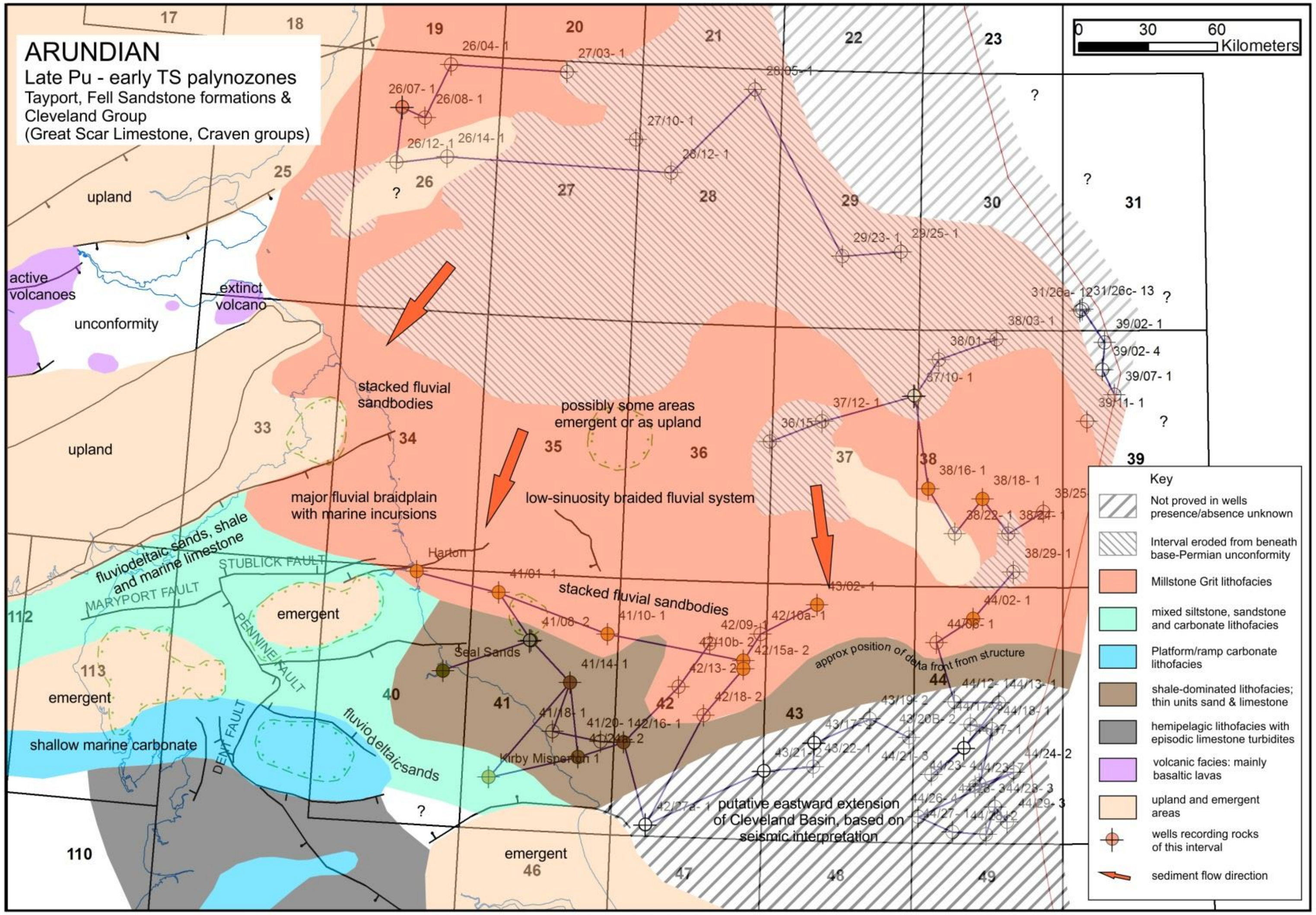

Figure 33 Arundian palaeogeography (Late Pu to early Ts Palynozone)

Arundian (Late Pu – early TS Palynozones)

Offshore: Fell Sandstone Formation and Cleveland Group.

Onshore: Fell Sandstone Formation, Lyne Formation (part), Ashfell Sandstone Formation, Great Scar Limestone and Craven groups.

Arundian times saw the first establishment of a major delta system across the region. A major, braided fluvial system, probably originating in the Caledonide Mountains far to the north-east spread coarse-grained sandstone in stacked, multi-storey sheets southward (Turner & Munro 1987; Morton et al., 2001). In north Northumberland the sand sheets probably fill an incised channel, but in the Northumberland Basin sandstone sheets are intercalated with marine siltstones and the Fell Sandstone Formation progrades south-westwards (Turner et al. 1997). The depositional extent of the sandstones across the Mid North Sea High is thought to be greater than that of the Tournaisian rocks, but nevertheless it is possible that ‘emergent’ areas existed.

In the Cleveland Basin, the time-equivalent rocks are the interbedded sandstone and mudstone of Cleveland Group A, and possibly the mudstone-dominated Cleveland Group B. The sandstone units probably represent the distal facies of the Fell Sandstone. The eastern extension of the Fell Sandstone “delta front” is inferred approximately from structural considerations. The sandstone present at the base of Kirby Misperton 1 well is inferred to be akin to the Ashfell Sandstone which is seen widely in northern England.

The Fell Sandstone has the potential as a reservoir rock. The mudstones of the Cleveland Group in the Cleveland Basin may be potential source rocks.

5.3 LATE ASBIAN (NM PALYNOZONE)

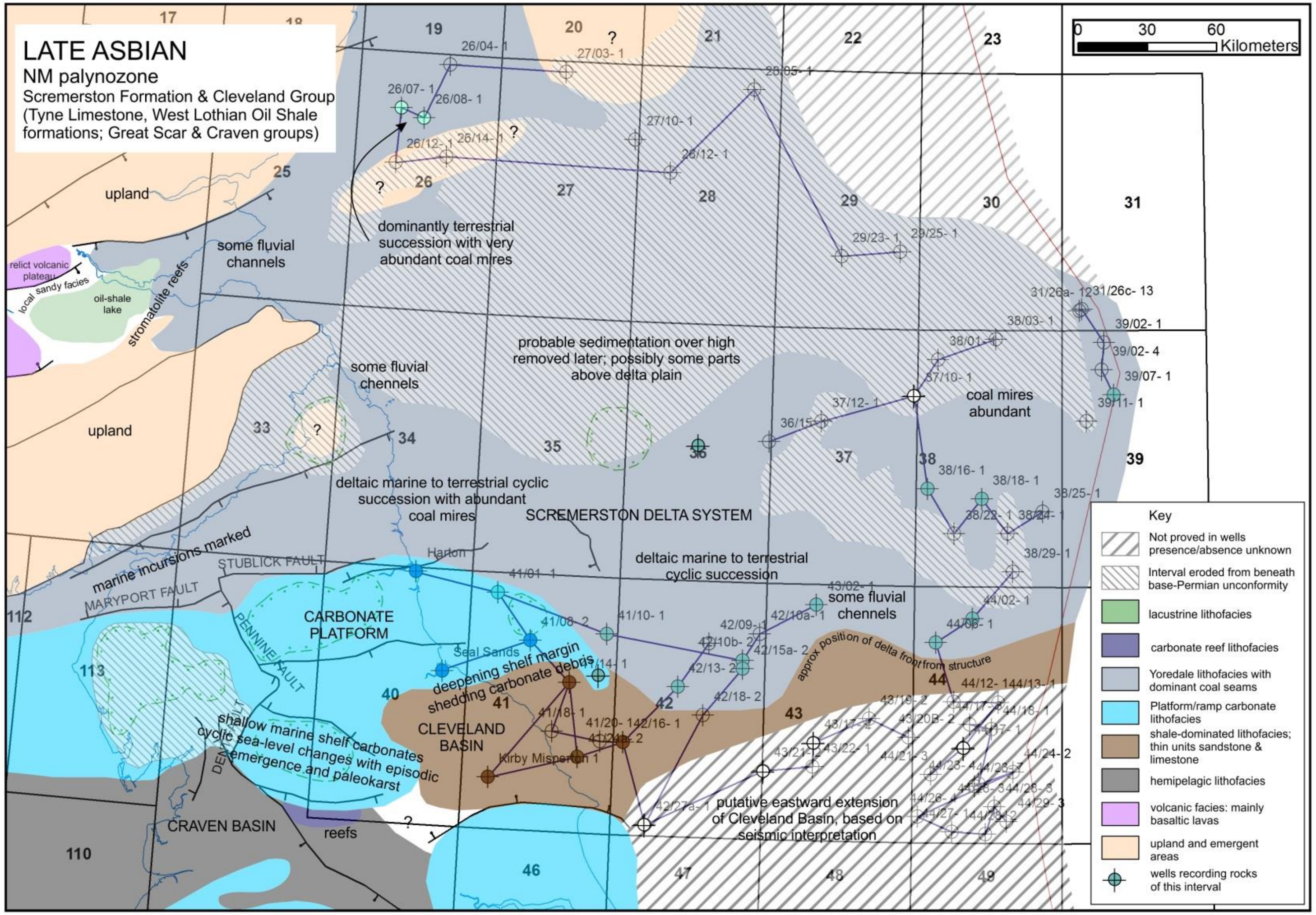

Figure 34 Late Asbian palaeogeography (NM Palynozone)

Late Asbian (NM Palynozone)

Offshore: Scremerston and Firth Coal formations, and Cleveland Group.

Onshore: Tyne Limestone Formation (Scremerston Member), West Lothian Oil Shale Formation, and Great Scar Limestone and Craven groups.

Late Asbian times saw the first development of the fluvio-deltaic Yoredale facies across 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 (e.g. Wright & Vanstone, 2001). In the Scremerston Formation the limestone part of the cycle is generally short lived and in north Northumberland and the Forth Approaches limestones may be very thin or absent from some cycles. In contrast, towards the south, limestones are thicker and more consistent. A large lake was established in the eastern part of the Midland Valley accumulating organic-rich muds that formed the West Lothian Oil Shale Formation. Though deposition was thought to be over the whole area, end Carboniferous to early Permian erosion has removed large parts of this formation from the Mid North Sea High region.

The previously emergent Lake District, Alston and Askrigg blocks onshore finally became submerged during Asbian time with the establishment of carbonate platforms. Abundant palaeokarstic surfaces in the upper Asbian Malham Formation (Great Scar Limestone Group) represent the emergent parts of the Yoredale cycles of the Scremerston Formation. Offshore, wells show the eastward extension of the platform across Quadrant 41, where limestone units interdigitate with Scremerston Formation to the north, and with mudstone-dominated succession of Cleveland Group C to the south.

With the abundance of coals in both the Firth Coal and Scremerston formations, and of oil shales in the Midland Valley, the rocks of this interval have the potential as hydrocarbon source rocks. Additionally, multistorey fluvial sandstone bodies with a ribbon-shaped geometry of up to 30 m thick and up to several kilometres wide and tens of kilometres long within the onshore Scremerston Member are potential reservoir rocks (Jones, 2008).

5.4 BRIGANTIAN (VF PALYNOZONE)

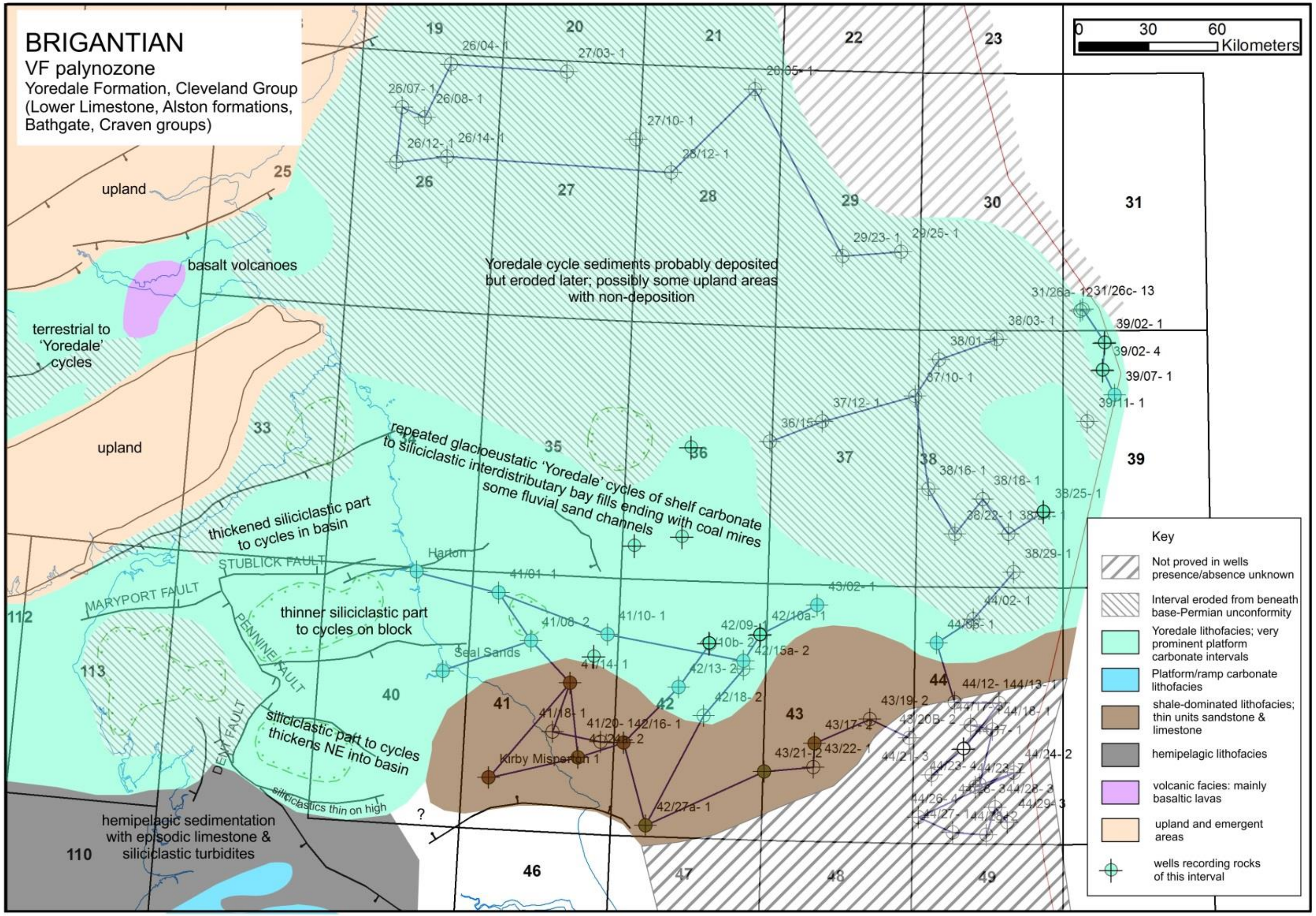

Figure 35 Brigantian palaeogeography (VF Palynozone)

Brigantian (VF Palynozone)

Offshore: Yoredale Formation and Cleveland Group.

Onshore: Lawmuir, Lower Limestone and Alston formations, Bathgate, Craven and Cleveland groups.

At the onset of Brigantian times, the carbonate platforms of northern England were overstepped by the Yoredale fluvio-deltaic clastic sediments and shallow carbonate seas. During this interval the marine limestones are at their thickest development. The thickest of these onshore is the Great Limestone, typically about 20 m thick which occurs at the top of the Alston Formation (Waters et al., 2011). A limestone of similar thickness seen in wells offshore in Quadrants 41-42 may be its correlative (Collinson, 2005). Onshore, the siliciclastic intervals within the cycles are thickened in the basins, whilst the limestones maintain fairly constant thickness across the area.

As with the Scremerston Formation, the Yoredale Formation has the potential for both source and reservoir rocks, though coals are typically less well developed. However, the limestones are characteristically dark and bituminous. Incised fluvial channel systems are of the same order of magnitude as those seen in the Scremerston Formation. In general, both the limestone and sandstone beds are typically sub-seismic resolution, except with the highest quality data.

5.5 PENDLEIAN (NC PARS PALYNOZONE)

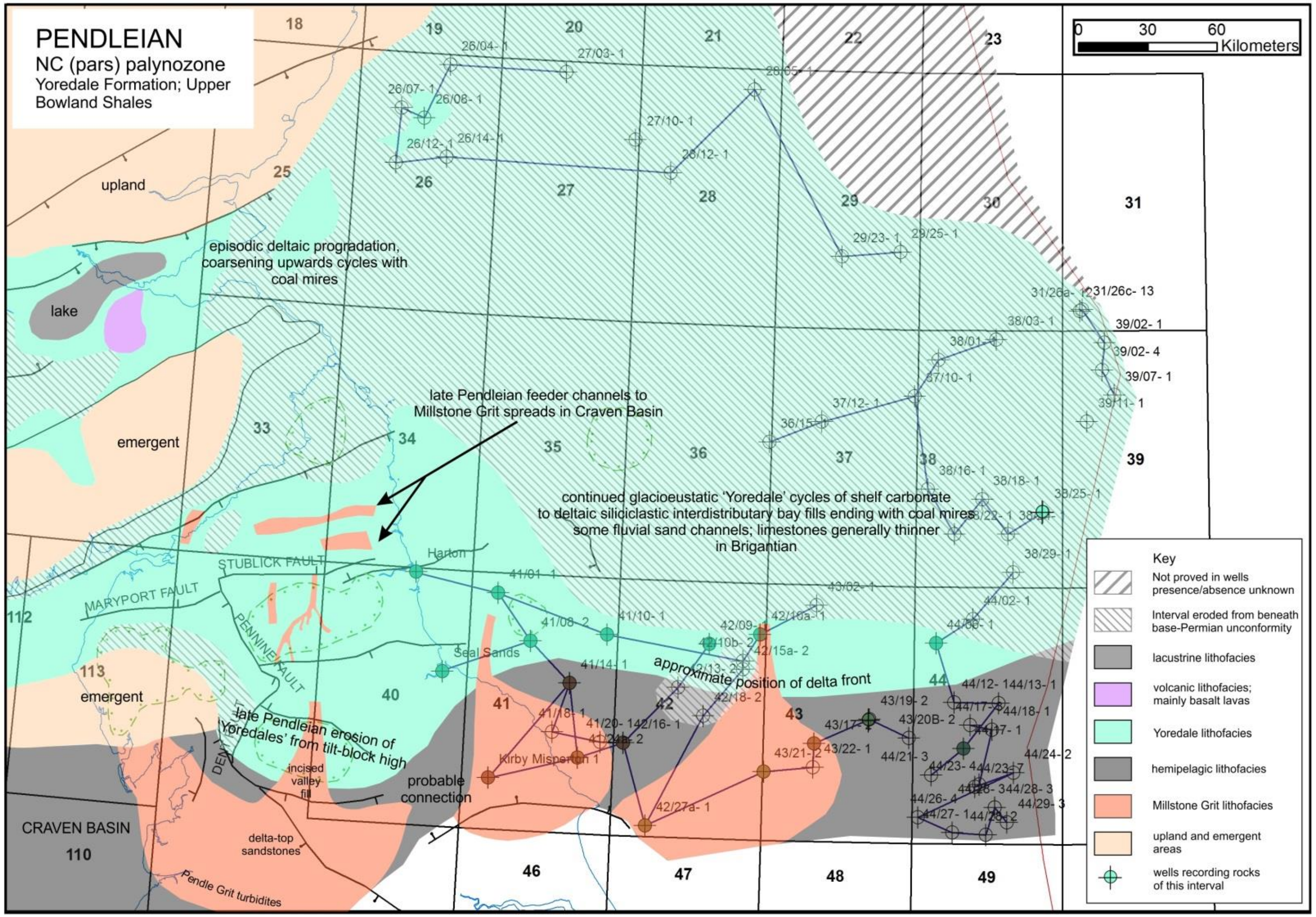

Figure 36 Pendleian palaeogeography (NC Palynozone).

Pendleian (NC Palynozone *pars*)

Offshore: Yoredale Formation, Cleveland Group (Upper Bowland Shales)

Onshore: Limestone Coal, Upper Limestone, Alston, Stainmore and Pendleton formations; Craven Group (Bowland Shale Formation)

The Yoredale facies established earlier continued through Pendleian and Arnsbergian times, though here above the horizon of the lower Pendleian Great Limestone, the limestones are thinner and more difficult to recognise in the wells. Substantial areas of these rocks across the North Sea High were eroded away in Late Pennsylvanian and Early Permian times. 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). Similar spreads of sand are inferred to the east in the Cleveland Basin. Wells in the southern part of Quadrants 41-44 record high-gamma mudstones that may be correlated with the Upper Bowland Shales of the Craven Basin; this shows, perhaps for the first time, a link between the two basins.

The high gamma values for the Upper Bowland Shales offshore suggest that these rocks have the potential as source rocks.

5.6 KINDERSCOUTIAN (EARLY KV PALYNOZONE)

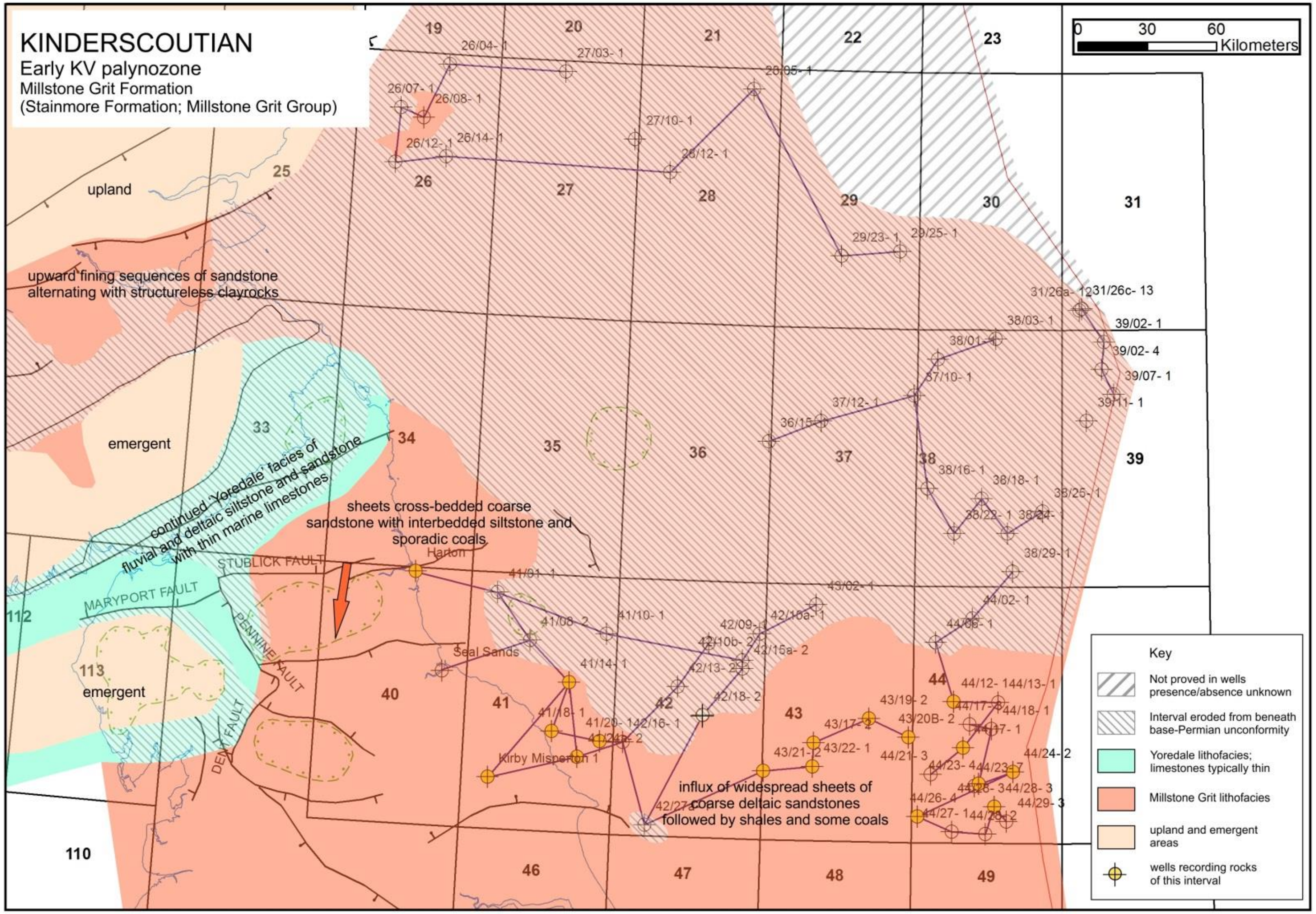

Figure 37 Kinderscoutian palaeogeography (Early KV Palynozone)

Kinderscoutian (early KV Palynozone)

Offshore: Millstone Grit Formation.

Onshore: Millstone Grit Group, Passage and Stainmore formations.

With renewed uplift in the Caledonide source region to the north-east, sheets of coarse deltaic sandstone spread across the entire region, though most of these rocks have been eroded from the Mid North Sea High region during Late Pennsylvanian and Early Permian times (Hallsworth & Chisholm 2003). The thick sand bodies are intercalated with increasing thicknesses southwards of siltstone and claystone, seat-earths and coals. In contrast, Yoredale facies rocks (Stainmore Formation) continued to dominate in the Northumberland basin (Waters et al. 2014).

The sandstones of the Millstone Grit Formation are potentially reservoir rocks in the southern parts of Quadrants 41-44.

6 References

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

ANDERTON, R. 1985. Sedimentology of the Dinantian of Foulden, Berwickshire, Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* Vol. 76, 7-12.

ANDREWS, J. E., TURNER, M. S., NABI, G. AND SPIRO, B. 1991. The anatomy of an early Dinantian terraced floodplain: palaeo-environment and early diagenesis. *Sedimentology,* Vol. 38, 271-287.

ANDREWS, I. J. 2013. The Carboniferous Bowland Shale gas study: geology and resource estimation. British Geological Survey for Department of Energy and Climate Change, London, UK.

BANGAL, J.M., CLOWER, D.R., MORBEY, S.J. 1976, The Biostratigrahy of the interval 1650'-12549'from the Mobil 38/3-1 British North Sea Well. Robertson Research International Limited, *Report confidential to DECC/OGA*

BESLY, B., 2005. Late Carboniferous redbeds of the UK southern North Sea, viewed in a regional context. In: J. Collinson, D. Evans, D. Holliday and N. Jones (Editors), Carboniferous Hydrocarbon Geology: the southern North Sea and surrounding onshore areas. *Yorkshire Geological Society Occasional Publication Volume 7*, 225-226.

BRAND, P. J. 2011. The Serpukhovian and Bashkirian (Carboniferous, Namurian and basal Westphalian) faunas of northern England. *Proceedings of the Yorkshire Geological Society*, Vol. 58(3), 143-165.

BROWNE, M A E, MONAGHAN, A A, RITCHIE, J D, UNDERHILL, J R, HOOPER, M D, SMITH, R A, AND AKHURST, M C. 2003. Revised tectono-stratigraphical framework for the Carboniferous of the Midland Valley of Scotland, UK. XV International Congress on Carboniferous and Permian Stratigraphy, Utrecht, The Netherlands, 10–16 August 2003, 68–70.

BRUCE, D. AND STEMMERIK, L., 2003. Carboniferous. In: D. Evans, C. Graham, A. Armour and P. Bathurst (Editors), *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea*. The Geological Society of London, pp. 7-1: 7-11.

CAMERON, T. 1993a. 5. Carboniferous and Devonian of the southern North Sea. In: R. Knox and W. Cordey (Editors), Lithostratigraphical Nomenclature of the UK North Sea. *British Geological Survey.*

CAMERON, T. 1993b. 4. Triassic, Permian and Pre-Permian (Central and Northern North Sea) . In: R. Knox and W. Cordey (Editors), Lithostratigraphical Nomenclature of the UK North Sea. *British Geological Survey.*

CATER, M.C., CHURCH J.W., GREENWOOD, R.J., HASKINS, C.W., 1967, The Micropalaeontology and Stratigraphy of the Amoshas 38/22- 1 North Sea Well. Robertson Research International Limited, *Report confidential to DECC/OGA*

COHEN, K.M., FINNEY, S.C., GIBBARD, P.L. & FAN, J.-X. 2013; updated The ICS International Chronostratigraphic Chart. *Episodes*, Vol. 36, 199-204.

COLE, J. M., WHITAKER, M., KIRK, M. and CRITTENDEN, S. 2005. Asequence-stratigraphical scheme for the Late Carboniferous, southern North Sea, Anglo-Dutch sector. In: J. Collinson, D. Evans, D. Holliday and N. S. Jones (Editors), Carboniferous Hydrocarbon Geology: the southern North Sea and surrounding onshore areas. *Yorkshire Geological Society Occasional Publication,* Volume 7, 75-104.

COLLINSON, J. D. 1988. Controls on Namurian sedimentation in the Central Province basins of northern England. In: Besly, B. M. and Kelling, G. (eds) *Sedimentation in a synorogenic basin complex: the Upper Carboniferous of Northwest Europe*, 86-101. Blackie & Son, London.

COLLINSON, J. D., JONES, C. M., BLACKBOURN, G. A., BESLY, B. M., ARCHARD, G. M AND MCMAHON, A. H. 1993. Carboniferous depositional systems of the Southern North Sea. In: Parker, J.R. (Editor) Petroleum geology of Northwest Europe: Proceedings of the 4th Conference, 677-687. Geological Society, London.

COLLINSON, J., 2005. Dinantian and Namurian depositional systems in the southern North Sea. In: J. Collinson, D. Evans, D. Holliday and N. Jones (Editors), Carboniferous Hydrocarbon Geology: the southern North Sea and surrounding onshore areas. *Yorkshire Geological Society Occasional Publication Volume 7,* 35-56.

DAY, J. B. W. 1970. Geology of the country around Bewcastle. *Memoir Geological Survey*. U.K

DAVYDOV, V.I., GLENISTER, B.F., SPINOSA, C., RITTER, S.M., CHEMYKH, V., WARDLAW, B. AND SNYDER, W., 1998. Proposal of Aidaralash as global stratotype section and point (GSSP) for base of the Permian System. *Episodes*, Vol. 21, 11-18.

DEAN, M., BROWNE, M., WATERS, C. AND POWELL, J. 2011. A lithostratigraphical framework for the Carboniferous successions of northern Great Britain (onshore). *British Geological Survey.*

DOORNENBAL, H. AND STEVENSON, A. (Editors). 2010. Petroleum geological atlas of the Southern Permian Basin area. Houten, the Netherlands, EAGE, 342pp.

GLENNIE, K., HIGHMAN, J. AND STEMMERIK, L., 2003. Periman. In: D. Evans, C. Graham, A. Armour and P. Bathurst (Editors). The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. *The Geological Society of London*, pp. 8-1: 8-44.

HALLSWORTH, C. R., AND CHISHOLM, J. I. 2008.Provenance of late Carboniferous sandstones in the Pennine Basin (UK) from combined heavy mineral, garnet geochemistry and palaeocurrent studies. *Sedimentary Geology*, Vol. 203(3), 196-212.

HAYWARD, R., MARTIN, C., HARRISON, D., VAN DORT, G., GUTHRIE, S. AND PADGET, N., 2003. The Flora field, blocks 31/26a, 31/26c, UK North Sea. Geological Society, London, Memoirs, 20(1), 549-555.

HEEREMANS, M., TIMMERMAN, M. J., KIRSTEIN, L. A. AND FALEIDE, J. I., 2004. New constraints on the timing of late Carboniferous-early Permian volcanism in the central North Sea. Special Publication Geological Society of London, 223: 177-194.

JOHNSON, G. A. L., SOMERVILLE, I. D., TUCKER, M. E. & COZAR, P. 2011. Carboniferous stratigraphy and context of the Seal Sands No. 1 Borehole, Teesmouth, NE England: the deepest onshore borehole in Great Britain. *Proceedings of the Yorkshire Geological Society*, Vol. 58, 173-196.

JONES, R. R., MCCAFFREY, K. J., IMBER, J., WIGHTMAN, R., SMITH, S. A., HOLDSWORTH, R. E., & WILSON, R. W. 2008. Calibration and validation of reservoir models: the importance of high resolution, quantitative outcrop analogues. *Geological Society, London, Special Publications*, 309(1), 87-98.

KOMBRINK, H., BESLY, B., COLLINSON, J.D., DEN HARTOG JAGER, D.G., DROZDZEWSKI, G., DUSAR, M., HOTH, P., PAGNIER, H.J.M., STEMMERIK, L., WAKSMUNDZKA, M.I. & WREDE, V., 2010. Carboniferous. In: Doornenbal, J.C. and Stevenson, A.G. (Eds): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten): 81-99.

LEEDER, M. R., FAIRHEAD, D., LEE. A., STUART, G. CLEMMEY, H., EL-HADDAHEH, B. AND GREEN, C. 1989. Sedimentary and tectonic evolution of the Northumberland Basin. *Proceedings of the Yorkshire Geological Society,* Vol. 47, 207-223.

LEEDER, M. R., AND BOLDY, S. A. R. 1990. The Carboniferous of the Outer Moray Firth Basin, quadrants 14 and 15, Central North Sea. *Marine and Petroleum Geology,* Vol. 7, 29-37.

LEEDER, M. R. AND HARDMAN, M. 1990. Carboniferous of the Southern North Sea Basin and controls on hydrocarbon prospectivity. In: Hardman, R. F. P. and Brooks. J. (Editors)

Tectonic events responsible for Britain's oil and gas reserves. Geological Society, London, Special Publication No. 55, 87 – 105.

MAHDI, S.A. 1992, Shell/Esso 41/1- 1 British North Sea well palynological analysis of the interval 2400' – 7050' (SWC), Simon-Robertson Limited, *Report confidential to DECC/OGA*

MARSHALL, J. AND HEWETT, T., 2003. Devonian. In: D. Evans, C. Graham, A. Armour and Bathurst (Editors), The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. *The Geological Society of London*, pp. 6-1: 6-16.

MARTIN, C. A., STEWART, S. A. AND DOUBLEDAY, P. A., 2002. Upper Carboniferous and Lower Permian tectonostratigraphy on the southern margin of the Central North Sea. *Journal of the Geological Society*, Vol. 159(6): 731-749.

MCLEAN, D. & NEVES, R. 1988. Palynostratigraphical review of the Carboniferous interval in well 26/7- 1. Arco British Ltd. *Report confidential to DECC/OGA*

MCLEAN, D., OWENS, B. & NEVES, R. 2005. Carboniferous miospore biostratigraphy of the North Sea. In: Collinson, J. D., Evans, D. J., Holliday, D. W. and Jones, N. S. (Editors). Carboniferous hydrocarbon geology; the southern North Sea and surrounding onshore areas. *Yorkshire Geological Society, Occasional Publication* Vol. 7, 13-24.

MCLEAN, D., 2013, Palynostratigraphy of the Carboniferous interval in southern North Sea well 37/10-1. MB Stratigraphy Ltd. Report No. 83a, *Report confidential to DECC/OGA.*

MONAGHAN, A.A., BROWNE, M.A. AND BARFOD, D.N., 2014. An improved chronology for the Arthur's Seat volcano and Carboniferous magmatism of the Midland Valley of Scotland. *Scottish Journal of Geology*, Vol. 50(2): 165-172.

MONAGHAN, A.A. 2014. The Carboniferous shales of the Midland Valley of Scotland: geology and resource estimation. British Geological Survey for Department of Energy and Climate Change, London, UK.

MORTON, A. C., CLAOUÉ-LONG, J. C., & HALLSWORTH, C. R. 2001. Zircon age and heavy mineral constraints on provenance of North Sea Carboniferous sandstones. *Marine and Petroleum Geology*, Vol. 18(3), 319-337.

PEARCE, T. J., MCLEAN, D., WRAY, D., WRIGHT, D. K., JEANS, C. J. AND MEARNS, E. W. 2005. Stratigraphy of the Upper Carboniferous Schooner Formation, southern North Sea: chemostratigraphy, mineralogy, palynology and Sm-Nd isotope analysis. In: J. Collinson, D. Evans, D. Holliday and N. Jones (Editors), Carboniferous Hydrocarbon Geology: the southern North Sea and surrounding onshore areas. *Yorkshire Geological Society Occasional Publication* Volume 7, 165-182.

PHILLIPS, J. 1836. Illustrations of the geology of Yorkshire. Part II. The Mountain Limestone district. John Murray, London.

ROBSON, D. A. 1956. A sedimentary study of the Fell Sandstone of the Coquet Valley, Northumberland. *Quarterly Journal of the Geological Society*, Vol. 112: 241-262

SCOTT, W. B. 1986. Nodular carbonates in the Lower Carboniferous, Cementstone Group of the Tweed Embayment, Berwickshire: evidence for a former sulphate evaporite facies. *Scottish Journal of Geology*, Vol. 22, 325-345.

SMITHSON, T. R., WOOD, S. P., MARSHALL, J. A. E., CLACK, J.A., 2012. Earliest Carboniferous tetrapod and arthropod faunas from Scotland populate Romer's Gap. *Proceedings of the National Academy of Sciences*, Vol.109, 4532-4537.

STEPHENSON, D., LOUGHLIN, S. C., MILLWARD D., WATERS, C. N. AND WILLIAMSON I. 2003. *Carboniferous and Permian Igneous Rocks of Great Britain, North of the Variscan Front.* Geological Conservation Review Volume 27. Joint Nature Conservation Committee: Peterborough. 374 pp.

STEPHENSON, M. H., WILLIAMS, M., MONAGHAN, A. A., ARKLEY, S., SMITH, R. A., DEAN, M. T., BROWNE, M. A. E. & LENG, M. J. 2004. Palynomorph and ostracod biostratigraphy of the Ballagan Formation, Midland Valley of Scotland, and elucidation of intra-Dinantian unconformities. *Proceedings of the Yorkshire Geological Society*, Vol. 55, 131-143.

STONE, P., MILLWARD, D., YOUNG, B., MERRITT, J. W., CLARKE, S. M., MCCORMAC, M., AND LAWRENCE, D. J. D. 2010. British Regional Geology: Northern England (Fifth edition). (Keyworth, Nottingham: British Geological Survey).

TURNER, B. R. AND MONRO, M. 1987. Channel formation and migration by mass-flow processes in the Lower Carboniferous fluviatile Fell Sandstone Group, northeast England. *Sedimentology*, Vol. 34(6), 1107-1122.

TURNER, B. R., DEWEY, C., AND FORDHAM, C. E. 1997. Marine ostracods in the Lower Carboniferous fluviatile Fell Sandstone Group: evidence for base level change and marine flooding of the central graben, Northumberland Basin. *Proceedings of the Yorkshire Geological and Polytechnic Society*, Vol. 51, No. 4, pp. 297-306

TREWIN, N.H. AND BRAMWELL, M.G., 1991. The Auk Field, Block 30/16, UK North Sea. *Geological Society, London, Memoirs*, 14(1): 227-236.

VAN ADRICHEM BOOGAERT, H.A. & KOUWE, W.F.P., 1993-1997. [Stratigraphic unit]. In: Stratigraphic Nomenclature of the Netherlands. https://www.dinoloket.nl/tayport-formation-ortp

WARD, J. (1997). Early Dinantian evaporites of the Easton-1 well, Solway basin, onshore, Cumbria, England. In: Meadows N S and others (editors) Petroleum Geology of the Irish Sea and adjacent areas. Geological Society, London, Special Publications No 124, 277-296.

WATERS, C N, AND DAVIES, S J. 2006. Carboniferous extensional basins, advancing deltas and coal swamps. 173-223 in *The Geology of England and Wales* (Second edition). BRENCHLEY, P J, and RAWSON, P F (editors). (The Geological Society London.)WATERS, C. N., BROWNE, M. A. E., DEAN, M. T. AND POWELL, J. H., 2007. Lithostratigraphical framework for Carboniferous successions of Great Britain (Onshore). *British Geological Survey Research Report*, RR/07/01. 60pp.

WATERS, C. N. 2011. A revised correlation of Carboniferous rocks in the British Isles. *Geological Society of London*.

WATERS, C. N., MILLWARD, D., THOMAS, C. W. 2014 The Millstone Grit Group (Pennsylvanian) of the Northumberland-Solway Basin and Alston Block of northern England. *Proceedings of the Yorkshire Geological Society*, Vol. 60 (1), 29-51.

WRIGHT, V. P. AND VANSTONE, S. D. 2001. Onset of Late Palaeozoic glacio-eustasy and the evolving climates of low latitude areas: a synthesis of current understanding. *Journal of the Geological Society*, Vol. 158(4), 579-582.

WHITEHURST, J. 1778. An enquiry into the original state and formation of the earth. London.

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 & 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)		*Gastrioceras listeri*		
		G2	*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				
	Arundian	BB	*Bollandites-Bollandoceras*		
	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	XII	NBM		*Potonieisporites novicus-bhardwajii-Cheiledonites major*	
	Stephanian B		ST		*Angulisporites splendidus-Latensina trileta*	
	Barruelian, Cantabrian		OT		*Thymospora obscura-T. thiessenii*	
WESTPHALIAN	Asturian	XI				
	Bolsovian	X	SL		*Torispora securis- T. laevigata*	
	Bolsovian, Duckmantian	IX, VIII	NJ		*Microreticulatisporites nobilis-Florinites junior*	
	Duckmantian, Langsettian	VII, VI	RA		*Radiizonates aligerens*	
	Langsettian	SS	SS		*Triquitrites sinani-Cirratriradites saturni*	
NAMURIAN	Yeadonian, Marsdenian	FR	FR		*Raistrickia fulva-Reticulatisporites reticulatus*	
	Kinderscoutian	KV	KV		*Crassispora kosankei-Grumosisporites varioreticulatus*	
	Alportian, Chokierian	SO	SO	SR	*Lycospora subtriquetra-Kraeuselisporites ornatus*	*L. subtriquetra-Cirratriradites rarus*
	Arnsbergian			SV		*L. subtriquetra-Apiculatisporis variocorneus*
		TK	TK		*Mooreisporites trigallerus-Rotaspora knoxi*	
	Pendleian	NC	CN	Vm	*Reticulatisporites carnosus-Bellispores nitidus*	*Verrucosisporites morulatus*
VISEAN	Brigantian			Cc		*Cingulizonates* cf. *capistratus*
		VF	VF		*Tripartites vetustus-Rotaspora fracta*	
	Asbian	NM	NM	ME	*Raistrickia nigra-Triquitrites marginatus*	*Murospora margodentata-Rotaspora ergonulii*
				DP		*Tripartites distinctus-Murospora parthenopia*
		TC	TC		*Perotrilites tessellatus-Schulzospora campyloptera*	
	Holkerian, Arundian	Pu	TS		*Knoxisporites triradiatus-Knoxisporites stephanephorus*	
	Arundian, Chadian		Pu		*Lycospora pusilla*	
TOURNAISIAN	Courceyan	CM	CM		*Schopfites claviger-Auroraspora macra*	
			PC		*Spelaeotriletes pretiosus-Raistrickia clavata*	
		VI	BP		*Spelaeotriletes balteatus-Rugospora polyptycha*	
			HD		*Kraeuselisporites hibernicus-Umbonatisporites distinctus*	
			VI		*Vallatisporites vallatus-Retusotriletes incohatus*	