Revised stratigraphic framework of pre-Westphalian Carboniferous petroleum system elements from the Outer Moray Firth to the Silverpit Basin, North Sea, UK.

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Abstract

Spatially and temporally variable Tournaisian to Namurian Carboniferous fluvial, fluvio-deltaic, platform carbonate and shale-dominated basin sedimentary successions up to 3.5 km thick are preserved in a complex series of basins from the Outer Moray Firth (Quadrant 14) to the Silverpit Basin (Quadrant 44). Differences in stratigraphical nomenclature in the areas surrounding the Mid North Sea High and onshore, and sparse biostratigraphical data have hindered systematic regional understanding of the timing and controls on stacked source and reservoir-rock intervals.

Over 125 well re-interpretations, tied to seismic interpretations, provide evidence of the inception and extent of a delta system. Regional time-slices highlight a long-lived laterally equivalent basinal, mud-rich succession across Quadrants 41-44. They also show that the Outer Moray Firth to the Silverpit Basin was part of the same sedimentary system up to at least Namurian times. All of this is placed within a simplified stratigraphical framework.

Keywords: Mississippian, Mid North Sea High, stratigraphy, palaeogeography

Supplementary material: Appendix 1 containing the stratigraphic intervals interpreted on each well and which intervals have biostratigraphic control. Also supplemental figures 1 and 2 are larger scale versions of Fig. 6-8 in the paper is available at

Westphalian gas prone rocks of the Southern North Sea have been the focus of Carboniferous hydrocarbon exploration and production in the North Sea (Cameron 1993a; Bruce & Stemmerik 2003; Underhill 2003; Kombrink *et al.* 2010). In recent years, there has been growing interest in older Carboniferous strata, with production from the Yoredale Formation in the Breagh Field (Symonds *et al.* 2015), and increasing interest in Namurian and older deeper water systems (Rodriguez *et al.* 2014), and offshore equivalents of the Bowland Shale Formation, highlighted for unconventional exploration (Andrews 2013). In response to the Wood Review (Wood 2014), and following consultation with industry, the British Geological Survey led the 21st Century Exploration Roadmap (21CXRM): Palaeozoic Project to provide regional interpretations of Devonian and Carboniferous petroleum systems from south of the Mid North Sea High to the Moray Firth and East Shetland Platform (Monaghan *et al*. 2017).

This paper re-assesses the stratigraphy and facies architecture of the pre-Westphalian Carboniferous strata in the North Sea, integrating and summarizing results from the detailed lithostratigraphical descriptions contained in the 21CXRM project reports (Whitbread & Kearsey 2016; Kearsey *et al.* 2015). More than 550 wells drilled in the study area penetrate Palaeozoic strata, and of these, 125 wells contain long sections through the Devonian or Carboniferous sequences. These 125 wells have been re-interpreted, incorporating biostratigraphical information, and integrated with seismic and gravity interpretations from Arsenikos *et al.* (this volume). Utilizing sedimentological interpretations from well records and onshore datasets, the regional facies architecture of the North Sea sedimentary system from the early-mid Carboniferous (Tournaisian to Namurian) from the Outer Moray Firth Basin to the Silverpit Basin is described in a series of time-slices. The laterally and temporally variable sedimentary facies that developed in response to active tectonism, varying sediment supply and glacio-eustatic sea-level variation is rationalized within an integrated model of the Carboniferous system to aid exploration in these areas.

Background

The geological evolution of the Carboniferous succession beneath the North Sea has been interpreted previously in a number of key publications. Cameron (1993b) described the lithostratigraphy of the Devonian to Permian rocks to the north of the Mid North Sea High and Cameron (1993a), Bruce & Stemmerik (2003), and Kombrink *et al.* (2010) detailed that to the south. Cameron's (1993a) scheme for the Pennsylvanian rocks of Quadrants 41–44 was modified subsequently by Besly (2005). South of the Mid North Sea High (Fig. 1), Collinson (2005) interpreted the depositional systems of the Mississippian and early Pennsylvanian age strata in Quadrants 41–43. To the north of the Mid North Sea High, strata of Carboniferous age are only preserved offshore in the east of the region in Quadrants 14, 15, 20, 21, 26, 27 and 29 (Fig. 1). Leeder & Boldy (1990) undertook a regional assessment of Carboniferous strata, based on analysis of wells in Quadrants 14 and 15. However, poor well coverage between Quadrants 14–15 and south of the Mid North Sea High has limited the degree to which it has been possible to correlate the Carboniferous of the North Sea as a whole. Together with a lack of published biostratigraphical studies, this has led to various stratigraphical schemes and has hindered regional interpretation.

By contrast, there are extensive studies of the onshore geology of the Devonian and Carboniferous of the Midland Valley of Scotland and northern England. Recent summaries of the lithostratigraphy, palaeogeography and tectonic evolution, for example are by Chadwick *et al.* (1995), Browne *et al.* (1999), Read *et al.* (2002), Trewin & Thirlwall (2002), Waters & Davies (2006) and Stone *et al.* (2010). The Carboniferous stratigraphy detailed in these accounts has been summarized further, along with that offshore, by Waters *et al.* (2011). The revision of the onshore lithostratigraphy is based on the distribution of the predominant lithofacies associations throughout the sequence, thus unifying, as far as is practicable, the many previous regional schemes (Browne *et al.* 2003; Waters *et al.* 2007; Dean *et al.* 2011).

Our study retains the offshore scheme more familiar to the hydrocarbons industry, making comparison with the onshore equivalents where appropriate. We use a biostratigraphical time-slice approach to outline the spatial extent of time-equivalent sedimentary facies interpretations from well records and onshore outcrops. Data integration reveals the large-scale sedimentary architecture and we attempt, at a high level, to unify the system as a whole.

Methods

Many of the 550 wells that have penetrated Devonian or Carboniferous rocks in Quadrants 14–44 contain only a short succession of these strata and their distribution is uneven (Fig. 2), with very few located outside of Quadrants 14–15 (Outer Moray Firth) and Quadrants 41–44 (south of the Mid North Sea High). Of these wells, 125 had sections of Carboniferous strata greater than 100 m or were long enough to identify stratigraphical units. Of those, 69 had biostratigraphical control, predominately in the form of unpublished palynology reports (Fig. 2, Appendix 1).

The subset of 125 wells formed the basis for the re-interpretation of the sedimentary facies and stratigraphy in this study. A set of key onshore wells provided a link with the offshore stratigraphy. 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 (Andrews 2013). In Scotland, the Firth of Forth 1 and Milton of Balgonie 1 wells were considered (see Monaghan 2014).

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 tops/bases in completion reports and in published papers were reassessed, and modified with new biostratigraphical information or interpretations informed by regional study. Seismic interpretations (Arsenikos *et al.* 2016) were also used to aid well interpretation.

This study had access to all company biostratigraphical reports stored on the UK Oil and Gas Data (CDA) portal (www.ukoilandgasdata.com), previously unreleased British Geological Survey palynological reports, and data donated by sponsors of the 21CXRM Palaeozoic project. The CDA reports cited in this paper are released documents from www.ukoilandgasdata.com. The biostratigraphical reports vary in date of completion, amount and quality of the data and the interpretation that they contain (Appendix 1), resulting in uncertainty in the precise biostratigraphical age of parts of the succession. Where multiple interpretations exist, the most modern interpretation was taken. Ambiguities in the biostratigraphical ages were analysed against the sedimentology and seismic picks (see Arsenikos *et al.* this volume), and the most parsimonious solution used. The miospore biozones for the Carboniferous have been revised several times. Waters *et al*. (2011) listed how the older nomenclature ("former index”) correlates with the newer nomenclature ("index"). In Appendix 1, we differentiate between the former and current index where possible. A critical appraisal of the biostratigraphical data would probably refine the results presented in this paper further, but could not be completed within the timescale of the 21CXRM Project.

Stratigraphical framework

Eight Tournaisian (lowest Carboniferous) to Kinderscoutian (middle Namurian) lithostratigraphical units were identified in wells in the study area. In chronological order (from oldest to youngest), the Tayport, Fell Sandstone, Scremerston and Millstone Grit formations occur to the north and south of the Mid North Sea High (Figs 3, 4), whereas the Cementstone, Firth Coal and Yoredale formations, and the Cleveland Group were more locally restricted (Figs 3, 4). Many of these units comprise different facies but are time equivalent (Fig. 5).

Tayport Formation

The Tayport Formation is proved in wells in Quadrants 12, 14, 15, 20 and 21 in the Outer Moray Firth and West Central Shelf (e.g. Fig. 6 and 7). It is also interpreted in wells in Quadrants 36, 37, 38, 42 and 44 (Fig. 3) near the Dogger High.

Alternations of sandstone and mudstone characterize the Tayport Formation north of the Mid North Sea High (Cameron 1993a). The sandstone units are predominantly 15 m thick (Bruce & Stemmerik 2003). In Quadrants 14–15 the formation also may contain sporadic tuffaceous and rhyolitic beds, typically 1 – 5 m thick (Cameron 1993a); examples occur in well 15/25b- 1a.

South of the Mid North Sea High, the Tayport Formation is known 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’ (Van Adrichem Boogaert & Kouwe 1993-1997a). The sandstone beds, 2 – 5 m thick, are interbedded with claystone and siltstone. The presence of thin limestone beds has also been inferred from the wireline logs.

In the Outer Moray Firth Basin, the Tayport Formation is thought to be least 500 m thick (Cameron 1993b) and spans the Devonian/Carboniferous boundary. It has a latest Famennian to Tournaisian age, proved palynologically (LN and CM biozones) in well 15/25b- 1a (CDA unknown date). South of Quadrants 14 and 15, the Tayport Formation is at least 350 m thick (42/10b- 2, Fig. 6) and where dated, is latest Devonian in age. The most southerly occurrence of the Tayport Formation in well E06-01 in the Dutch sector (Van Adrichem Boogaert & Kouwe 1993-1997a), is inferred to be late Famennian based on the occurrence of *Retispora lepidophyta* (Van Adrichem Boogaert & Kouwe 1993a) which indicate the LL to LN biozones.. The only occurrence of Tournaisian Tayport Formation south of Quadrants 14 and 15 is in well 37/10- 1 (McLean 2013). The proximity of this well to the Dogger High may suggest that this occurrence represents a localized debris fan, because the surrounding Tournaisian sedimentary rocks in wells such as 37/25- 1 and 38/24- 1 are of the Cementstone Formation (Fig. 5).

The sandstone units are fluvial channel fills, partly stacked to form thicker sandstone units in the northern area and representing a proximal fluvial channel system with associated overbank deposits; evidence for marine influence is sparse (Leeder & Boldy 1990). In the south, the claystone and siltstone are floodplain deposits, their red colouration suggesting that they are well-drained palaeosols. There appears to have been no development of wetlands or mires in this succession (Van Adrichem Boogaert & Kouwe 1993-1997a).

Cementstone Formation

The Cementstone Formation occurs in wells around the southern margin of the Mid North Sea High (Figs 3, 6). It has been picked from seismic sections across the Mid North Sea High and in the Forth Approaches basin (Fig. 3; Arsenikos *et al*. this volume). The Cementstone Formation is composed of red/brown and green/grey siltstone and thin, fine to coarse-grained sandstone units up to 25 m thick, with dolostone and limestone beds between 1 and 4 m thick (Cameron 1994). The gamma log signature varies abruptly, alternating between low and high gamma values; except for some sandstones, bed thickness rarely exceeds 5 m, reflecting the thinly interbedded character. The thickness of the Cementstone Formation proved in wells is from 100 to 500 m.

The conformable top and basal contacts of the formation occur in well 42/10b- 2 (Fig. 6). The formation is also present in the Dutch well E06-01 (Van Adrichem Boogaert & Kouwe 1993-1997b). Its onshore correlatives are the Ballagan and Lyne formations of the Midland Valley, Tweed and Northumberland basins (Dean *et al.* 2011; Waters *et al.* 2011). The Ballagan Formation consists of fluvial sandstone, coastal plain siltstone interbedded with lacustrine siltstone and dolostone (cementstone); the last, typically in beds up to 1 m thick, was probably deposited in saline lagoons (Anderton 1985; Scott 1986; Andrews *et al.* 1991, Bennett et al. 2016; Kearsey et al. 2016). The Lyne Formation represents more sustained marginal marine intervals (Leeder 1974; Ward 1997) with marine limestones 1 – 10 m thick in cyclical sequences of sandstone, siltstone and mudstone.

The Cementstone Formation is dated palynologically as Tournaisian to early Visean in wells 38/22- 1, 41/01- 1, 43/02- 1 (Cater *et al.* 1967; Mahdi 1992; Fig. 5). In the base of well 26/07- 1 in the Forth Approaches Basin a limestone unit yielded spores from the Pu Biozone, suggesting that this well penetrated the very top of the Cementstone Formation (Appendix 1). This mirrors the range found in the Midland Valley of Scotland and adjacent Tweed Basin, where the Ballagan Formation extends from the VI (Smithson *et al*. 2012) to the lower Pu Biozone (McAdam *et al.* 1985).

Fell Sandstone Formation

The Fell Sandstone Formation is found onshore in Northumberland (NE England) and Berwickshire (SE Scotland). There is no sedimentary equivalent in the Midland Valley of Scotland, where Chadian to Asbian volcanic activity gave rise to the extrusive igneous rocks of the Garleton Hills, Arthur’s Seat and Clyde Plateau volcanic formations (Stephenson *et al.* 2004; Monaghan & Parrish 2006). The Fell Sandstone Formation occurs widely across the south of the Mid North Sea High (Cameron 1993a; Bruce & Stemmerik 2003; Collinson 2005), but prior to this study it had not been identified to the north. It is now interpreted in well 26/07- 1 in the Forth Approaches Basin and in wells in Quadrants 20 and 21, east of the Grampian High and Halibut Horst (Figs 3, 6).

The Fell Sandstone Formation has been picked in seismic surveys over the eastern side of the Mid North Sea High and in the North Dogger and Q29 basins (Fig. 3; Arsenikos *et al.* this volume) and is assumed to extend across the southern edge of the Mid North Sea High to the outcrops in Northumberland (Fig. 3). The formation is not identified north of quadrants 21 and 22.

The Fell Sandstone Formation is typically characterized by massive sandstone units up to 50 m thick, interbedded with units up to 20 m thick of siltstone and mudstone. The gamma log signature is dominated by low gamma sandstones, which commonly have a more ‘blocky’ signature compared with sandstones in formations above and below (Fig. 6 and 7). In some wells (e.g. 26/07- 1) the succession comprises clean sandstone with only thin intercalations of siltstone and mudstone, but elsewhere (42/10b- 2) the succession is more heterogeneous (Fig. 6).

The Fell Sandstone Formation ranges from 200 to 500 m thick in wells. Beyond well data coverage, seismic data (Arsenikos *et al.* this volume) show that it thickens into basins and has an average thickness of 500 m. The contrast between the seismic response from the sandstone facies of the Fell Sandstone Formation and the response from coal facies of the overlying Scremerston Formation produces an event that can be picked in seismic from the Forth Approaches basin to quadrants 41–44 (Arsenikos *et al.* this volume; Arsenikos *et al.* 2015). This has allowed offshore intersections of the Fell Sandstone to be identified with confidence in wells such as 38/16-1 (Fig. 6). The base of the Fell Sandstone Formation is taken at the abrupt downward change from thick sandstone units to interbedded sandstone, siltstone and mudstone of the underlying Cementstone Formation, a transition that is marked by a distinct change in wireline log character (Fig. 6). The top of the formation is taken at the top of the uppermost thick sandstone unit below a coal-bearing succession of interbedded mudstone, siltstone and sandstone of the Scremerston Formation.

Palynological evidence from close to the top and base of the Fell Sandstone in 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) (Fig. 5). Onshore, in the Northumberland-Solway Basin the base of the Fell Sandstone Formation is diachronous, becoming generally younger toward the south-west (Stone *et al.* 2010). In the Forth Approaches Basin, a unit previously identified as the Tayport Formation in well 26/7- 1 by Cameron (1993a) and Bruce & Stemmerik (2003) is re-interpreted in this study as the Fell Sandstone Formation, based, on the mid Holkerian (V3a) to Chadian (V1a) age (Welsh & Walton 1985) and the 'blocky' gamma signature.

The Fell Sandstone Formation is interpreted to be the deposit of a major sandy braided-river system (Turner & Monro 1987) formed of stacked multi-storey channel fills and separated by mudstone intervals, some of which contain marine microfaunas and are thought to represent maximum flooding surfaces (Turner *et al.* 1997; Collinson 2005).

Scremerston Formation

The Scremerston Formation is interpreted in wells and has been picked on seismic data from Quadrants 37, 38, 39, 40, 41, 42, 43 and 44 (Fig. 3D). It is likely to be continuous in extent from the Northumberland coast across the eastern side of the Mid North Sea High and along its south-eastern margin (Cameron 1993a). It has also been identified in wells 26/07- 1 and 26/08- 1 in the Forth Approaches (Fig. 6). Previously classified in these wells as the Firth Coal Formation by Cameron (1993b) and Bruce & Stemmerik (2003), these rocks have a Holkerian to Asbian biostratigraphical age and a range of facies, within that of the Scremerston Formation, and are herein assigned to this formation. It has been picked in seismic data over the eastern side of the Mid North Sea High and in the Q29 and North Dogger Basins (Fig. 3; Arsenikos *et al.* this volume). The Scremerston Formation broadly coincides with the onshore Tyne Limestone Formation, which includes the locally dominant Scremerston Coal Member (Dean *et al.* 2011; Waters *et al.* 2011).

The Scremerston Formation is characterized by coal-rich intervals within a mudstone-dominated sequence, with alternations of sandstone, siltstone and some thin limestone or dolostone beds (Cameron 1993b; Bruce & Stemmerik 2003). Upward coarsening parasequences are sporadically present within the upper parts of the formation, but it contains many more and thicker coals than the overlying Yoredale Formation. Coals are up to 3 m thick in exceptional cases, but are typically about 1 m thick (Cameron, 1993b). The sandstone units probably include both single and stacked channel fills. Homogeneous dark grey and black mudstones generate a uniformly high gamma-log response (Fig. 6). In wells the Scremerston Formation ranges in thickness from 90 to 1000 m, similar to that interpreted from seismic data

(Arsenikos *et al.* this volume). This is significantly thicker than the onshore Scremerston Coal Member at Berwick-upon-Tweed, which is about 300 m thick (Waters *et al.* 2011; Stone *et al.* 2010).

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 (e.g. wells 41/01- 1, 43/02- 1 and 44/06- 1) it is solely Asbian in age. The two wells in the Forth Approaches have yielded palynomorphs of late Arundian and Holkerian to late Asbian age (McLean & Neves 1988).

The Scremerston Formation represents widespread delta plain and back-swamp mire environments (Bruce & Stemmerik 2003). In the Forth Approaches basin it is thought to be dominantly terrestrial, whereas south in Quadrants 41–42 it is a deltaic, marine to terrestrial cyclic succession (Kearsey *et al.* 2015).

Firth Coal Formation

The Firth Coal Formation is found in Quadrants 14 and 15 (e.g. wells 14/04- 1, 15/19- 1 and 15/19- 2), in the Witch Ground Graben and may extend northward. The unit has also been interpreted in wells in the Outer Moray Firth Basin in Quadrants 20 and 21 (e.g. wells 20/04a- 2 and 20/15- 1, Fig. 7). It has been picked in seismic data in the Outer Moray Firth Basin (Fig. 4; Arsenikos *et al.* this volume).

The formation is lithologically similar to the Scremerston Formation, consisting of coal-rich intervals within a mudstone-dominated succession, with alternations of sandstone, siltstone and some thin limestone (Fig. 6 and 7). A 6 m thick bed of oil shale has been identified in well 20/10a- 3, highlighting that organic-rich lacustrine units are present offshore. As well data are sparse in the Forth Approaches and towards the Outer Moray Firth, a more extensive oil-shale source rock basin may exist there but this remains unproved. The Firth Coal Formation is 200 m thick on average. Though the top contact has been eroded from beneath the Permian or Cretaceous unconformities, the Firth Coal Formation is significantly thinner than the Scremerston Formation and was deposited over a longer time interval. It is retained as a separate unit in this northern area.

The oldest palynological date for the Firth Coal Formation is early Visean (Chadian, Pu Biozone) in well 15/17- 1A (Bagnall *et al.* 1973) and in other wells in Quadrants

14 – 15 it spans the Chadian to Pendleian (Bagnall *et al.* 1973; Fig. 6 and 7). The youngest biostratigraphical age is late Namurian (Kinderscoutian, KV Biozone) in well 20/15- 2 (Harris *et al.* 1998) and the range in Quadrants 20 and 21 is Holkerian to Kinderscoutian. This would make some parts of the Firth Coal Formation equivalent in age to the Yoredale and Millstone Grit formations to the south.

A sand-rich facies is identified in the Firth Coal Formation in Quadrants 14, 15 and 21 e.g. wells 15/19- 1 (Fig. 7), 15/19- 3, 15/21a- 7, 20/04a-2 and 21/13b- 1a. Here, massive sandstone units up to 40 m thick are separated by siltstone and mudstone interbeds 10 – 20 m thick. By contrast, wells close by, such as 15/19- 2 (Fig. 6), contain strata of equivalent age, but are represented by a mudstone-dominated, coal-rich succession. This suggests rapid lateral facies change and that the sand-rich facies represents channel infill. The mudstone-dominated facies of the Firth Coal Formation is found both below (20/04a- 2, Fig. 7) and above (e.g. 15/19- 3) the sand-rich facies. The sand-rich facies is similar in character to the Fell Sandstone Formation. However, seismic data do not show these to be laterally extensive units (Arsenikos *et al.* 2016). Also, in well 21/13b- 1a, Asbian – Pendleian (NM-NC biozone) palynomorphs (Appendix 1) have been recorded which suggest that, in that well, it is equivalent in age to the Yoredale Formation south of the Mid North Sea High. However, it is possible that some examples of the sand-rich facies are of Fell Sandstone age and represent the feeder channels to the delta front.

Yoredale Formation

The Yoredale Formation occurs in wells 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 (Fig. 4). The Yoredale Formation is equivalent to onshore sedimentary rocks in northern England comprising stacked sequences of ‘Yoredale cycles’ (Cameron 1993a). This includes that part of the Tyne Limestone Formation that lies above the Scremerston Coal Member, along with the Alston and Stainmore formations (Dean *et al.* 2011; Waters *et al.* 2011). Onshore, the Great Limestone is the thickest limestone of the Alston Formation at about 20 m and is the uppermost bed of the Alston Formation. A comparably thick limestone is seen in some wells offshore (e.g. 44/06- 1) and is equated with the Great Limestone, indicating that the equivalent of the Stainmore Formation is preserved in part to the south of the Mid North Sea High (Kearsey *et al.* 2015).

The offshore Yoredale Formation comprises a repeated cyclic succession commencing with a 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. 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 (Fig. 6; Maynard & Dunay 1999). 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. In many wells the Yoredale Formation is truncated by the unconformity beneath the base of the Permian strata, but where not eroded it is greater than 800 m thick (Jones 2007).

Compared with the underlying Scremerston Formation, the Yoredale Formation contains thicker limestones and the common presence of coarsening-upwards parasequences (Stephenson *et al.* 2010). Though present at outcrop onshore, typically beneath the limestones, the thin coals within the Yoredale Formation are mostly below wireline logging resolution.

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.

Cleveland Group

The Visean and lower Namurian succession in the central and southern part of Quadrants 41–44 is characterized by apparently homogenous units of shale exceeding 100 m thick, interbedded with cycles of limestone, sandstone, mudstone and sporadic coals that are similar to those seen in the Scremerston and Yoredale Formations to the north (Figs 4, 8). A similar succession, about 1400 m thick, occurs in the onshore well Kirby Misperton 1. The base of the succession is not proved and the Millstone Grit Formation overlies it. In the upper part, there is a high gamma unit of black shale that Cameron (1993a) termed the Bowland Shales Formation. We refer to the high gamma unit as the Upper Bowland Shales in order to avoid direct comparison with the eponymous formation, which has a wider definition and age range across northern England (Aikenhead et al. 1992).

Emphasizing the shale-rich character of this succession Kearsey *et al*. (2015) assigned these rocks informally to the existing Cleveland Group. Johnson *et al.* (2011) introduced this term for the thick, middle Visean shale-rich succession proved in Seal Sands No. 1 well. However, significant intervals in that well comprise Yoredale facies, and parts are also coal-rich; as a result, this succession has only superficial resemblance to that seen in Kirby Misperton and offshore. Though the term Cleveland Group may not be entirely appropriate given the small amount of data available to date and its difference from the original 'type' section, we prefer to retain the informal term here, redefining it as above.

Based on gross characteristics, Kearsey *et al*. (2015) divided the group in Kirby Misperton 1 into six informal units, 'A' to 'E' and the Upper Bowland Shales which lie below unit 'E'. High gamma values characterizing the Upper Bowland Shales show this unit to be a consistent marker across all of the wells penetrating the group (Fig. 7). The Upper Bowland Shales has an average thickness of 60 m in wells and ranges in thickness from 17-136 m. As suggested by Kearsey *et al*. there is potential for correlation of shale packages beneath the Upper Bowland Shales. For example, unit 'D' shows consistent characteristics across many of the wells, though the units A-C below this cannot be easily correlated between wells. Based on dip measurements previously Collinson (2005) had suggested that the interval identified by Kearsey *et al*. as Cleveland 'D' in well 43/21- 2 represents a slumped slope deposit. Furthermore, coals are absent from the lower part of the group in Kirby Misperton 1, suggesting that this part represents a mudstone-dominated pro-delta and basinal succession. By contrast, the apparent intercalation of Yoredale-type facies with homogenous shales implies alternations between the delta top and slope-and-basin facies. In this respect, the northernmost well of this group, 41/14- 1, and Seals Sands No. 1 more resemble the Yoredale Formation.

Though miospore assemblage data are few (Appendix 1), a consistent pattern of ages emerges across the area. Samples from wells 41/14- 1, 41/24a- 2 and Kirby Misperton 1 indicate that the Cleveland Group units below the Upper Bowland Shales lie within the Arundian to Brigantian interval. The overlying Upper Bowland Shales contain upper Brigantian and Pendleian miospores. The highest unit (E) in the group in Quadrant 41 and Kirby Misperton 1 has yielded Pendleian to Arnsbergian ages, whereas in Quadrant 43 this range extends into the Alportian.

The succession above the Upper Bowland shales, seen in wells 43/21- 2, 43/17- 2 and 44/17- 1, may be the lateral equivalent of the Epen Formation in the Dutch sector (Van Adrichem Boogaert & Kouwe 1993-1997c). This similarity is best seen in well Nagele-1 and Luttelgeest-1 in the Netherlands. The Epen Formation also contains the Geverik Member, which is a high gamma shale similar to the Upper Bowland Shales (Van Adrichem Boogaert & Kouwe 1993-1997c). However, the Geverik Member has been dated as Arnsbergian to Alportian, younger than the Upper Bowland Shales and so may not represent the same anoxic event. The high gamma values of the Upper Bowland Shales similarly occur within the Bowland–Hodder unit of the onshore Craven Basin, providing a critical correlation with that basin through into the Irish Sea (Andrews 2013; Wakefield *et al*. 2016). This also shows that the Cleveland and Craven Basins became linked during deposition of the Upper Bowland Shales (Andrews 2013).

Millstone Grit Formation

The Millstone Grit Formation is widespread south of the Mid North Sea High to the London-Brabant Massif (Cameron 1993a). It is interpreted in wells in Quadrants 40, 41, 42, 43 and 44 (Figs 4, 7; Cameron 1993a). A 126 m thick sandstone unit with a blocky gamma-ray trace recorded in well 26/08- 1 in the Forth Approaches Basin (Fig. 6 and 7) is tentatively correlated with the Passage Formation in the Midland Valley. The Passage Formation is approximately equivalent to the Millstone Grit Formation (Cameron, 1993a; Read *et al*. 2002; Waters *et al.* 2014).

The Millstone Grit Formation comprises cycles of sandstone, interbedded mudstone and siltstone, thin marine bands and sporadic thin coals (Cameron 1993a; Collinson 1988). The sandstone is typically coarse to very coarse grained with some units containing common ‘floating’ quartz pebbles (Cameron 1993a). It lacks the upward coarsening cycles with limestone of the Yoredale Formation. It ranges from 10 – 1027 m thick across the study area (Fig.8).

The offshore Millstone Grit Formation is Pendleian to Yeadonian in age. However, the base of the formation is markedly diachronous. Onshore, in the Craven Basin the lowest formations in the Millstone Grit Group are Pendleian in age (Aitkenhead *et al*. 2002), whereas in Northumberland the lowest unit is Kinderscoutian (Waters *et al.* 2014), which is comparable to that recorded in biostratigraphy logs offshore (Appendix 1).

Collinson (1988) interpreted the offshore Millstone Grit Formation as a succession of prograding fluvial and delta-front successions accumulating in basinal areas.

Discussion

Previously, the Mid North Sea High has been used to separate Carboniferous stratigraphical nomenclature to the north and south of it (Cameron 1993a, b; Bruce & Stemmerik 2003). However, Arsenikos *et al.* (in this volume) show that during the Carboniferous a series of basins underlay much of the area. It is also evident from wells in this study that the Tayport, Cementstone, Fell Sandstone, Scremerston and Millstone Grit formations are present to the north, south, and over large areas of the eastern side of the Mid North Sea High (Fig. 9). Although these units thin across this area (Arsenikos *et al.* in this volume), it is clear that the Mid North Sea High did not form a barrier to sedimentary systems during the Carboniferous.

This interpretation is supported by identification, in the Forth Approaches Basin, of the Fell Sandstone and Scremerston formations in wells (26/07- 1 and 26/08- 1) suggesting that it was part of the same fluvio-deltaic system extending to Quadrants 41-44 (Fig. 6). To the south, the Cleveland Group has been interpreted in wells as far east as Quadrant 44 suggesting that this marine basin is extensive (Figs 7, 8). Many of the formations are time equivalent and suggest that the southern Central North Sea was dominated by pro-delta and basinal successions from the Visean to the Namurian, while to the north, fluvial facies are more common.

Provenance of fluvial systems

Based on the regional tectonic history, it is suggested that the Carboniferous deltaic system is likely to have drained from the north within Laurussia in the early to mid-Carboniferous (Gilligan 1919 ; Cliff *et al.* 1991; Coward 1993, Morton *et al.* 2001). Establishing if the fluvial systems are sourced locally from upland areas such as the Grampian Highlands/Grampian High and Southern Uplands/offshore Mid North Sea High or from much farther northwards within the more northern parts of the Caledonian orogeny, is critical to understanding the size of this fluvial system. Leeder & Boldy (1990) suggested that the source of the Firth Coal Formation sediment was local, from the surrounding Grampian Highlands. However, zircon analysis has subsequently shown that the source region included a wide range of mid-Proterozoic and Archean rocks that are more likely from East Greenland, in addition to material derived locally (Morton *et al.* 2001). Morton *et al.* (2001) suggested that the zircon populations of the Firth Coal Formation are similar to those seen in the Namurian Ashover Grit and Rough Rock in the Pennine Basin, indicating a common provenance for both systems lying to the north of the modern North Sea. This finding supports the hypothesis presented here that the sand-rich facies of the Firth Coal Formation may represent feeder channel systems for the coeval Yoredale Formation and later Millstone Grit delta-front system south of the Mid North Sea High. In addition, using a multi-proxy provenance approach, Lancaster *et al.* (2017) suggested that the sand in the Millstone Grit Group in Yorkshire derived dominantly from the Greenland Caledonides, but with additional material from western Norway and NE Scotland.

The provenance of the Tournaisian and Visean sandstones is poorly constrained. Palaeocurrent analysis of the Fell Sandstone Formation in Northumberland indicates palaeoflow from the north-east (Robson 1956; Turner *et al.* 1997). The presence of the Fell Sandstone Formation as far north as Quadrants 20 and 21, and its co-existence with the age-equivalent siltstone dominated terrestrial succession and abundant coal mires of the Firth Coal Formation present to the north suggest the fluvial system has reached its apex point and become more channelized (Fig. 109b). This may indicate that in the Arundian, at least, the whole of the North Sea was part of the same fluvial system receiving sediment from the Caledonide mountains or from farther to the north.

Sedimentary basin evolution

High resolution, sequence stratigraphical examination of offshore wells was not attempted in this study because of the lack of correlative chronostratigraphical data and the regional scale. However, the onshore work of Church & Gawthorpe (1994), Hampson *et al.* (1996), Leeder & Stewart (1996), Davies (2008) and Stephenson *et al.* (2010) appears highly relevant to the Visean–Namurian delta plain to basinal setting. These studies use marine bands to identify transgressions and their erosion to identify the sequence boundaries; however, for this study, it is very difficult to consistently pick out such marine bands and correlate them between wells. Sequence stratigraphy could be applied if chronostratigraphical constraints were improved.

For the reasons given above, a sequence stratigraphical model for the Carboniferous has not been derived. Instead, the sedimentary facies interpretations are divided into selected time slices to create a regional palaeogeographical understanding of how the facies relate to each other and how the palaeogeography and sediment system evolved from the Tournaisian to Namurian (Fig. 10). The overall picture during the Mississippian and early Pennsylvanian is that there were two periods of voluminous sediment influx and large-scale progradation of the fluvial system in the Arundian and Kinderscoutian, possibly driven by uplift to the north (Coward 1993). Between these periods, gross sediment influx reduced and eustatic/climatic controls dominated.

Tournaisian

In the Tournaisian the fluvial Tayport Formation, which in the Devonian had been dominant south of the Mid North Sea High, became restricted to the Outer Moray Firth and some small areas near to basin highs. To the south, the coastal plain and marginal marine Cementstone Formation is interpreted as far south as Quadrant 41. The transition from Cementstone Formation to the Tayport Formation is not seen but occurs somewhere between the Quadrant 26 and 20-21 (Fig. 10a). However, an unconformity is identified in the underlying Upper Devonian in the area between the Grampian High and Forth Approaches Basin (Arsenikos *et al.* 2016).

Recent studies of the Ballagan Formation onshore near Berwick upon Tweed have shown the presence of a dynamic coastal plain dominated by overbank flooding, lakes, sabkhas and abundant palaeosols, and subjected to short episodes of marine flooding (Bennett *et al.* 2016, 2017; Kearsey *et al.* 2016). Seismic mapping shows the Tournaisian succession to thin against older rocks such as that of the granite-cored Dogger High, which was probably elevated above the coastal plain (Milton-Worssell *et al.* 2010; Arsenikos *et al.* this volume). On the south side of the Mid North Sea High limestones typically 1–4 m thick, but sporadically up to 10 m thick, and containing a generally restricted marine invertebrate fauna replace the ferroan dolostones that characterize the formation to the north. The limestones represent marine intervals and are characteristic of the Visean Lyne Formation in Northumberland (formerly Lower Border Group, *sensu* Day 1970).

Chadian – Holkerian

A major clastic system was established across the region by Arundian times (Fig. 10b). A braided fluvial system, probably originating in the Caledonide Mountains or farther to the north, spread coarse-grained sand in stacked, multi-storey sheets southward (Turner & Monro 1987; Morton *et al.* 2001). In north Northumberland the sand sheets probably fill an incised channel, but in the Northumberland Basin sandstone sheets in the upper part of the formation are intercalated with marine siltstones and the Fell Sandstone Formation progrades south-westwards (Turner *et al.* 1997).

The northernmost extent of the Fell Sandstone Formation is in Quadrants 20 and 21 (Fig. 5). To the north of this, in Quadrants 14 and 15, the Firth Coal Formation represents the alluvial plain developed upstream from the major braid plain, where coal mires, fluvial channel sandstones, and minor lacustrine units dominated.

To the south, in the Cleveland basin, time-equivalent rocks are the interbedded sandstone and mudstone of the oldest known part of the Cleveland Group, dominated by pro-delta and basal successions. The sandstone units probably represent the distal facies of the Fell Sandstone.

Asbian

By the late Asbian, coal mires and fluvial facies had developed within the Carboniferous basins from the Outer Moray Firth Basin to the southern edge of the Mid North Sea High (Fig. 10c).

Over Quadrants 26–44 the Scremerston Formation represents a range of depositional environments including fluvio-deltaic, lacustrine, wetland and marine-influenced bay deposits associated with a major deltaic system (Leeder & Boldy 1990; Leeder *et al.* 1989). Glacio-eustatic fluctuations in sea level affected the deltas with episodic rises in sea level flooding the area and allowing carbonates to be deposited (e.g. Wright & Vanstone 2001). Marine fauna found in the carbonate rocks suggest that they were formed at similar shallow water depth, regardless of whether the carbonate formed on the block or basin (Brand 2011). However, there are significant thickness changes in the clastic sediment between limestone units, across basin bounding faults. This is thought to be controlled by differential subsidence and syn-depositional faulting in the Northumberland Basin (Leeder *et al.* 1989) and may also have continued into the North Sea. In the Scremerston Formation, the limestone part of the cycle is generally short lived and in north Northumberland and the Forth Approaches Basin limestones may be very thin or absent from some cycles. In contrast, towards the south, limestones are thicker and more consistent, suggesting that there is greater effect of marine transgressions.

To the north of the Forth Approaches Basin, the Firth Coal Formation continued to be deposited. Asbian strata record the first dated occurrence of the Firth Coal Formation sand-rich facies (Fig. 6), which is contemporaneous with the coal-rich intervals. The occurrence of sand-rich lithofacies in the Firth Coal Formation indicates that there may have been large-scale channel systems running north to south across the area. In the south, in Quadrants 41–43, the mudstone-dominated succession in the lower part of the Cleveland Group was deposited in the Cleveland Basin (Fig. 5).

Brigantian

At the onset of Brigantian times, Yoredale-type fluvio-deltaic clastic sediments and shallow carbonate seas overstepped the Asbian carbonate platforms of the Alston and Askrigg blocks (Fig. 10d). In the Forth Approaches Basin, the Yoredale Formation was not deposited or was eroded subsequently, suggesting either that the basin was tectonically active at this time or sediment had bypassed it (See well 26/08- 1 in Figs 6, 9).

The position of the transition to the mudstone-dominated pro-delta and basinal succession of the Cleveland Group had not changed grossly since the Arundian. However, by Brigantian times, units of sandstone with subordinate interbedded mudstone, siltstone and some limestone were deposited (see Cleveland Group; Fig. 8), suggesting that the delta had prograded into the Cleveland Basin.

Pendleian

The Yoredale fluvio-deltaic clastic sediments and shallow carbonate seas continued to be deposited through Pendleian and Arnsbergian times (Fig. 10e). Substantial areas of these rocks across the Mid North Sea High were eroded away in late Pennsylvanian and early Permian times. Over time, fluvial, fine to medium-grained sandstones became progressively more significant within the succession. Incised fluvial-channel systems are of the same order of magnitude as those seen in the Scremerston Formation (Jones 2007; Waters *et al*. 2014). In general, both the limestone and sandstone beds are typically sub-seismic resolution, except with the highest quality data.

In Quadrants 20, 21, 14 and 15 siltstone-dominated terrestrial successions with abundant coal mires and fluvial channels continued through this period, with deposition of the Firth Coal Formation (Fig. 7).

In the Cleveland Basin a package of mudstones and silty mudstones with high gamma values (correlated to the Upper Bowland Shales, Fig. 8) has a late Brigantian to Pendleian age. This suggests that a link between the Cleveland and Craven basins were established for the first time in the Pendleian.

Arnsbergian – Kinderscoutian

The Arnsbergian sees the first occurrence of the Millstone Grit Formation in the North Sea. This is represented by sheets of deltaic coarse sand spreading from the north-east because of renewed uplift in the Caledonide source region (Hallsworth & Chisholm 2008). Through the Arnsbergian to the Alportian, the Millstone Grit Formation is inferred to have spread across much of the North Sea, filling the Cleveland Basin in the study area by the Kinderscoutian (Collinson 2005) (Fig. 10f). The Millstone Grit Formation was eroded from the Mid North Sea High during late Pennsylvanian and Early Permian times (Hallsworth & Chisholm 2008).

North of the Forth Approaches in quadrant 20, the long-established regime of coal mires and fluvial environments continued throughout this period (Fig. 10). After this time, either the younger Carboniferous sediments in the Outer Moray Firth Basin have been removed by erosion or deposition in these basins ceased after the Kinderscoutian.

Sedimentological controls on the petroleum system

The Visean and Namurian basinal facies have been proved to be a working petroleum system onshore in the East Midlands and Cleveland basins (Pletsch *et al.* 2010). Our study has identified that the Cleveland Basin extends eastwards at least as far as Quadrant 44, and that the organic-rich Upper Bowland Shales is present throughout (Monaghan *et al.* 2017). The lower–middle Carboniferous succession is more than 2 km thick in the south of Quadrants 41–44. The high gamma values for the Upper Bowland Shales offshore (Fig. 8) and source-rock geochemistry data for the Cleveland Group suggest that these rocks have the potential as source rocks although may overmature at deeper levels (Monaghan *et al.* 2017). Offshore, the Scremerston, Firth Coal, and to a lesser extent Yoredale, and Millstone Grit formations contain many coals which could also act as source rocks although this depends on their maturation history (Monaghan et al 2017). Previously, shales and coals of the Scremerston Formation have been documented as a rich potential source rock and are dominantly gas prone (Collinson *et al.* 1995). Mudstones in the Midland Valley equivalent of the Cementstone Formation, the Ballagan Formation, have low TOC values and probably do not have significant source-rock potential (Monaghan 2014).

The Fell Sandstone and Millstone Grit formations are dominated by fluvial sandstones up to 50 m thick that, depending on their physical properties, could act as reservoirs within the Carboniferous succession (Monaghan et al 2017). Also, the Scremerston, Firth Coal and Yoredale formations contain channel or deltaic coarse sandstone bodies, and intraformational seals could be provided by interbedded, extensive mudstones. Multi-storey, fluvial sandstone bodies with a ribbon-shaped geometry up to 30 m thick and up to several kilometres wide and tens of kilometres long are present in the Tyne Limestone Formation onshore (Jones 2007). The channel systems could also provide pathways to allow hydrocarbons generated in the

Cleveland Group to migrate up dip into the clastic succession (Monaghan *et al*. 2017).

North of the Forth Approaches Basin and in the Outer Moray Firth Basin the identification of the sand-rich facies within Firth Coal Formations suggests that significant channels are present in that unit, which could act as both intraformational reservoirs and as pathways for hydrocarbons generated from the coals to migrate into younger strata.

Conclusions

Wells from the Outer Moray Firth Basin to the Silverpit Basin that contain Carboniferous sedimentary rocks, for which just over half have biostratigraphical reports available, have been reinterpreted and integrated with seismic mapping. There is continuity between the sedimentary systems both sides of the Mid North Sea High, suggesting that in the Carboniferous these systems were linked.

The extent and inception of a long-lived Carboniferous fluvio-deltaic system and laterally equivalent basinal, mud-rich successions have been documented using a regional well dataset interpreted in a series of time-slices. Variations in the palaeogeography and facies architecture evolved in response to basin forming tectonic events, sea-level change and changes in sediment supply. Facies variations, which have resulted in complex nomenclatures, can be resolved into a stratigraphy utilizing newly released biostratigraphical data and a regional approach. Uncertainty has been reduced in the likely regional extent and character of coal, oil-shale and marine mudstone-bearing source-rock intervals (such as the Upper Bowland Shale, Scremerston, and Firth Coal formations). Understanding of the stratigraphical position and regional extent of potential reservoir intervals both in stacked fluvial (Fell Sandstone and Millstone Grit formations), and channel, systems (Yoredale, Scremerston and Firth Coal formations) has been improved.

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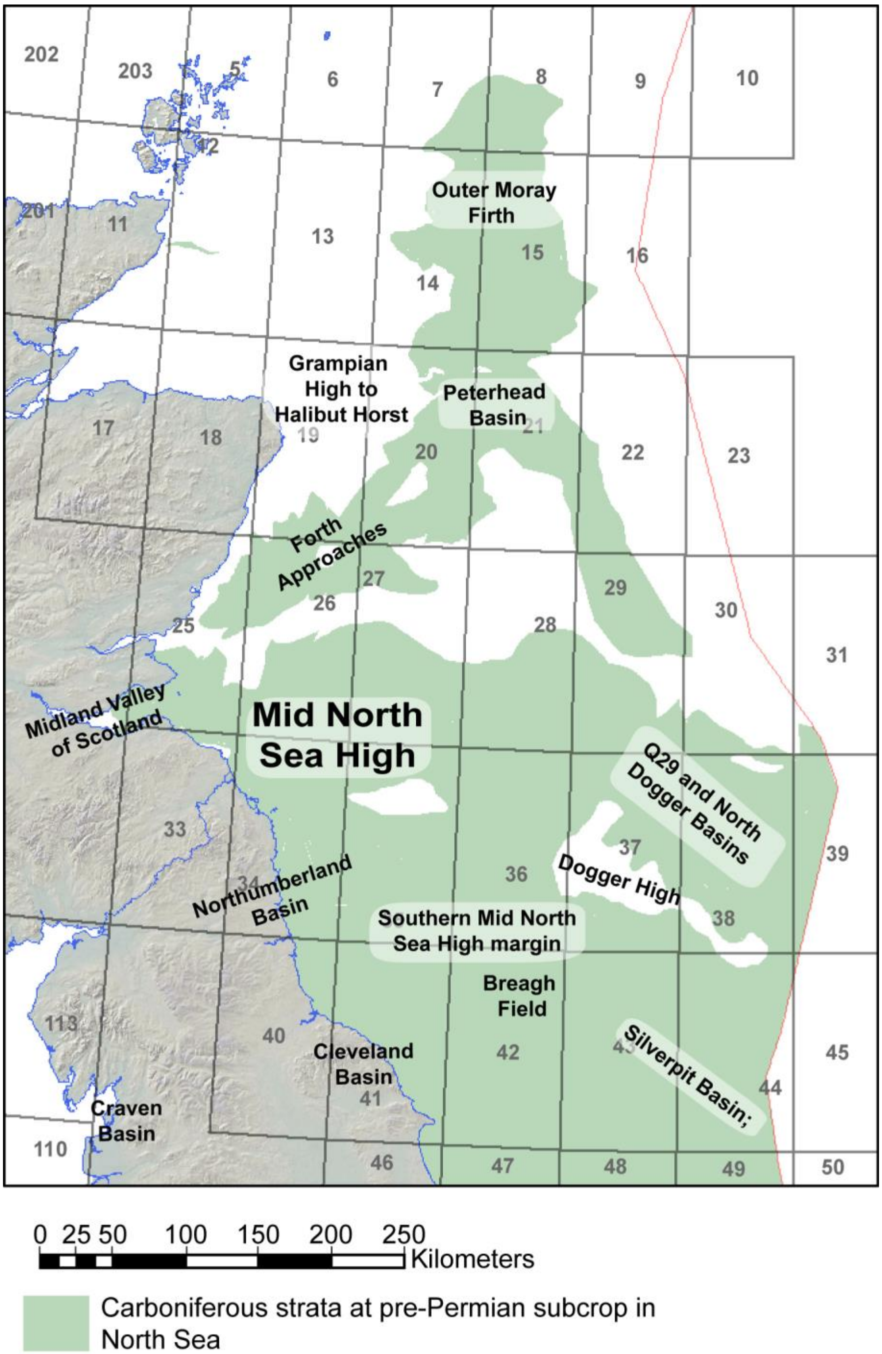

Fig. 1. Distribution of structural domains (including basins and highs) in the North Sea, as named in this study. It also shows the distribution of Carboniferous strata at subcrop. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EU and NEXTMap Britain elevation data from Intermap Technologies).

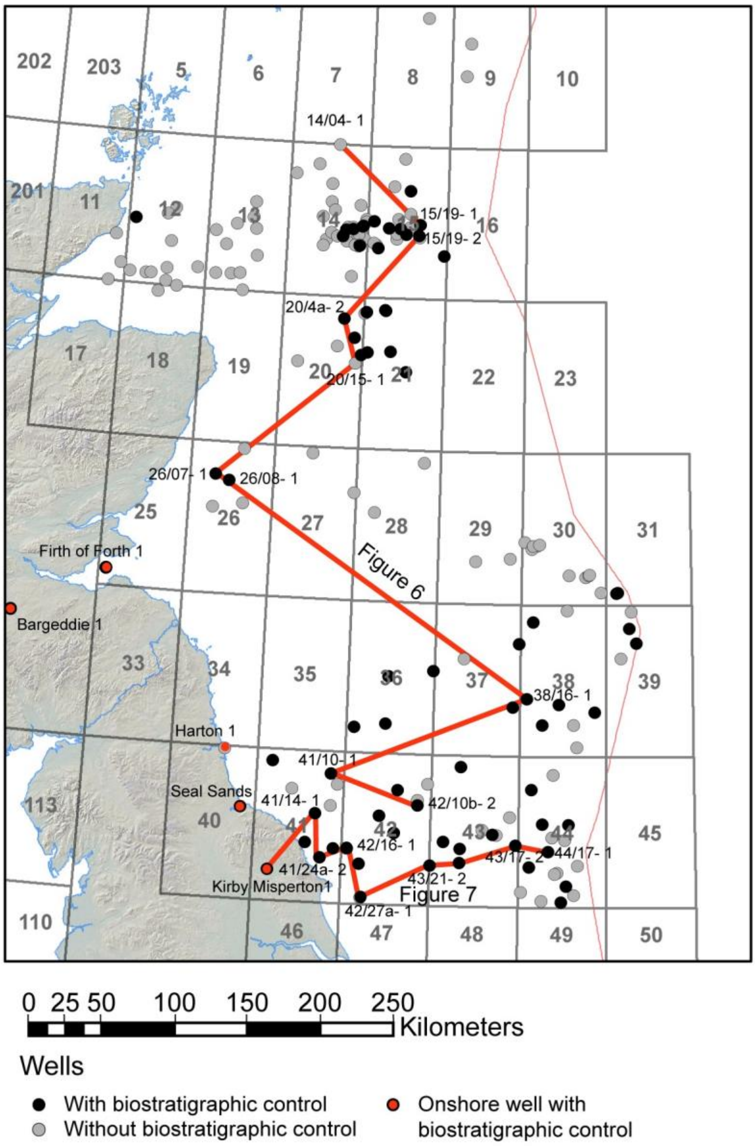

Fig. 2. Distribution of wells re-interpreted containing Carboniferous strata. Those wells that had biostratigraphical data are marked with a black circle. The paths of the correlation panels in Figs 6 and 7 are shown. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EU and NEXTMap Britain elevation data from Intermap Technologies).

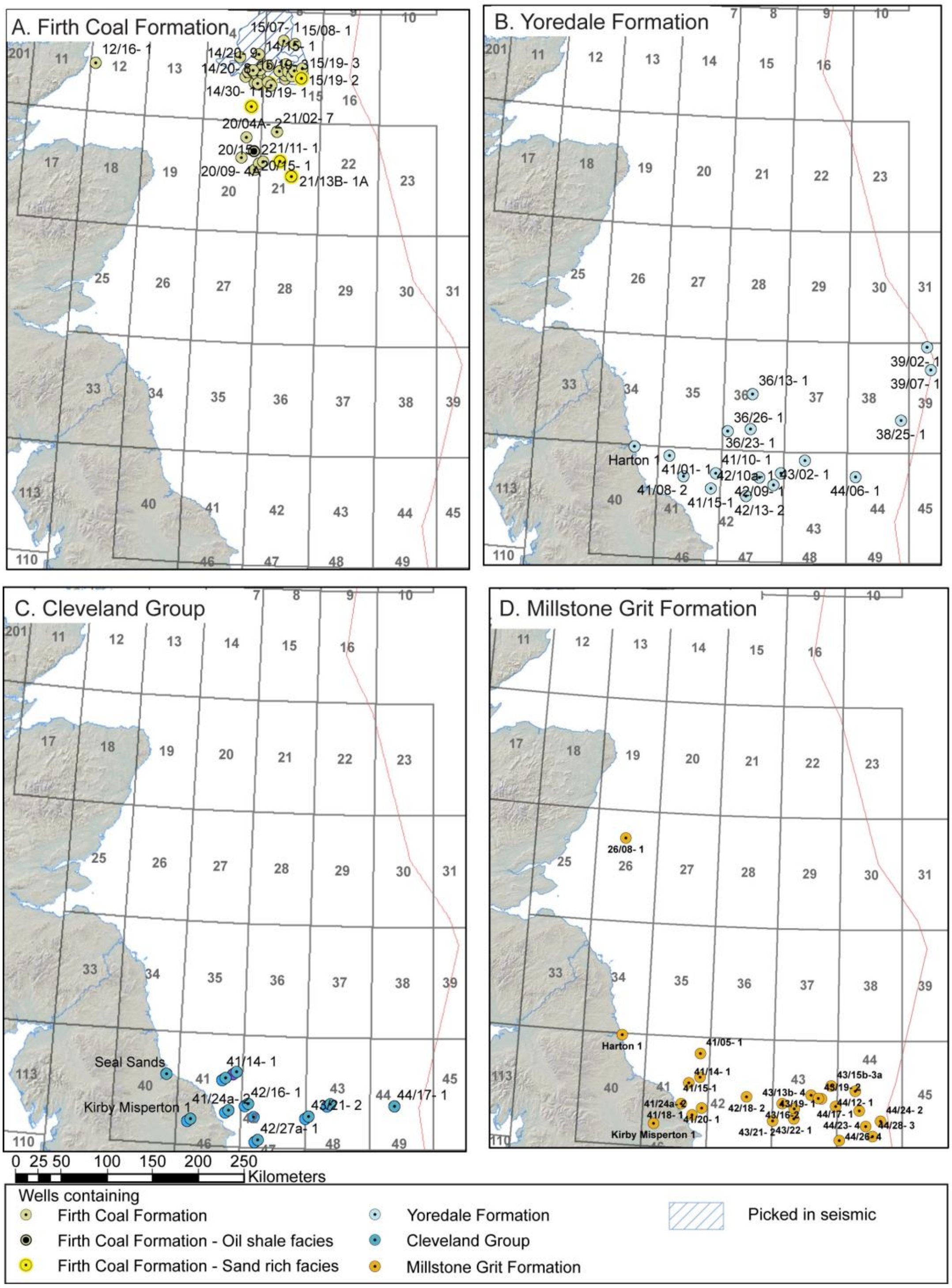

Fig. 3. The distribution of wells and extent of seismic picks of the (**a**) Tayport Formation (wells); (**b**) Cementstone Formation (wells); (**c**) Fell Sandstone Formation (wells and seismic picks); (**d**) Scremerston Formation (wells and seismic picks). For information on the seismic picks see Arsenikos *et al.* this volume. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EU and NEXTMap Britain elevation data from Intermap Technologies).

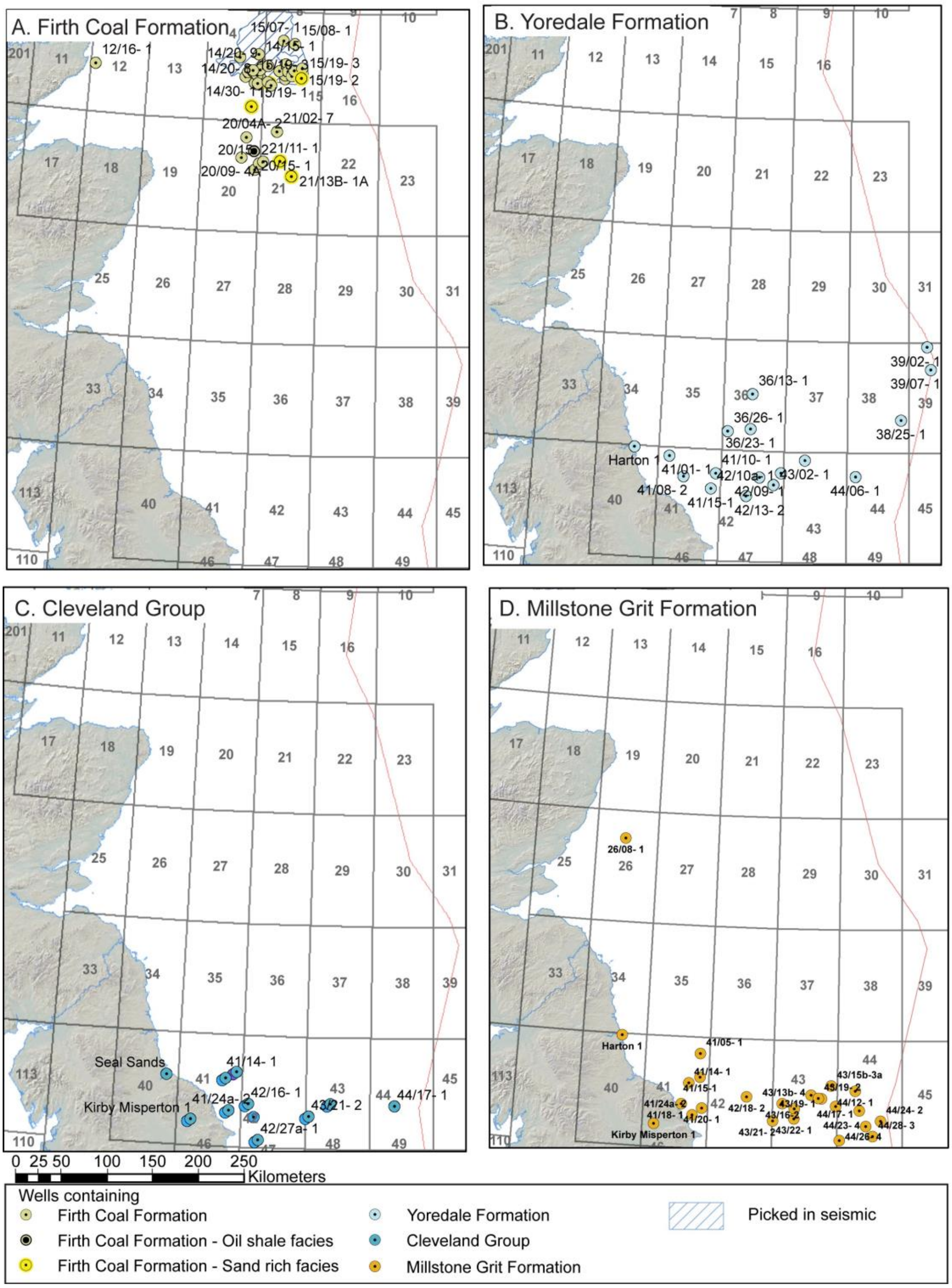

Fig. 4. The distribution of wells and extent of seismic picks of the (**a**) Firth Coal Formation (wells and seismic picks); (**b**) Yoredale Formation (wells); (**c**) Cleveland Group (wells); (**d**) Millstone Grit Formation (wells). For information on the seismic extent information, see Arsenikos *et al.* this volume. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EU and NEXTMap Britain elevation data from Intermap Technologies).

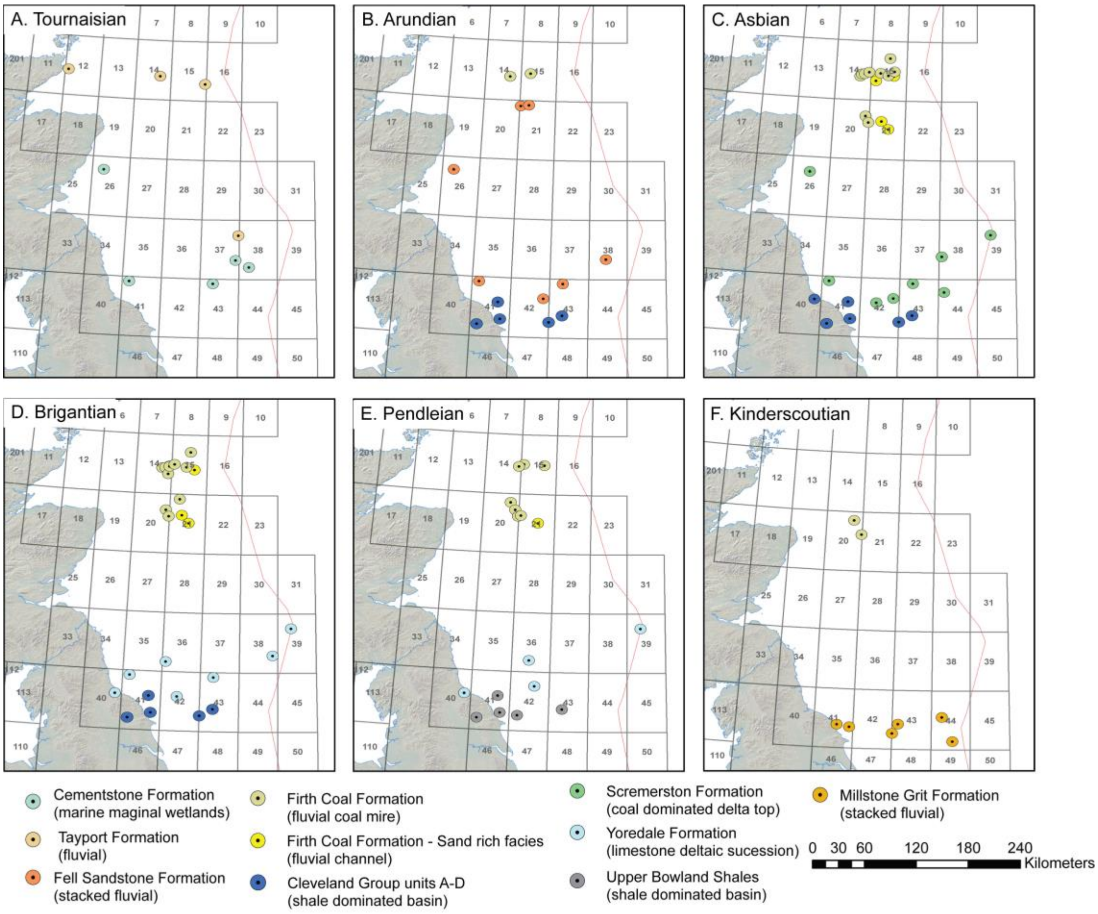

Fig. 5. Maps showing stratigraphic units proved in wells with biostratigraphical control in the (**a**) Tournaisian (earliest Carboniferous); (**b**) Arundian (early Visean); (**c**) Asbian (late Visean); (**d**) Brigantian (late Visean); (**e**) Pendleian (early Namurian); (**f**) Kinderscoutian (mid Namurian). Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EU and NEXTMap Britain elevation data from Intermap Technologies).

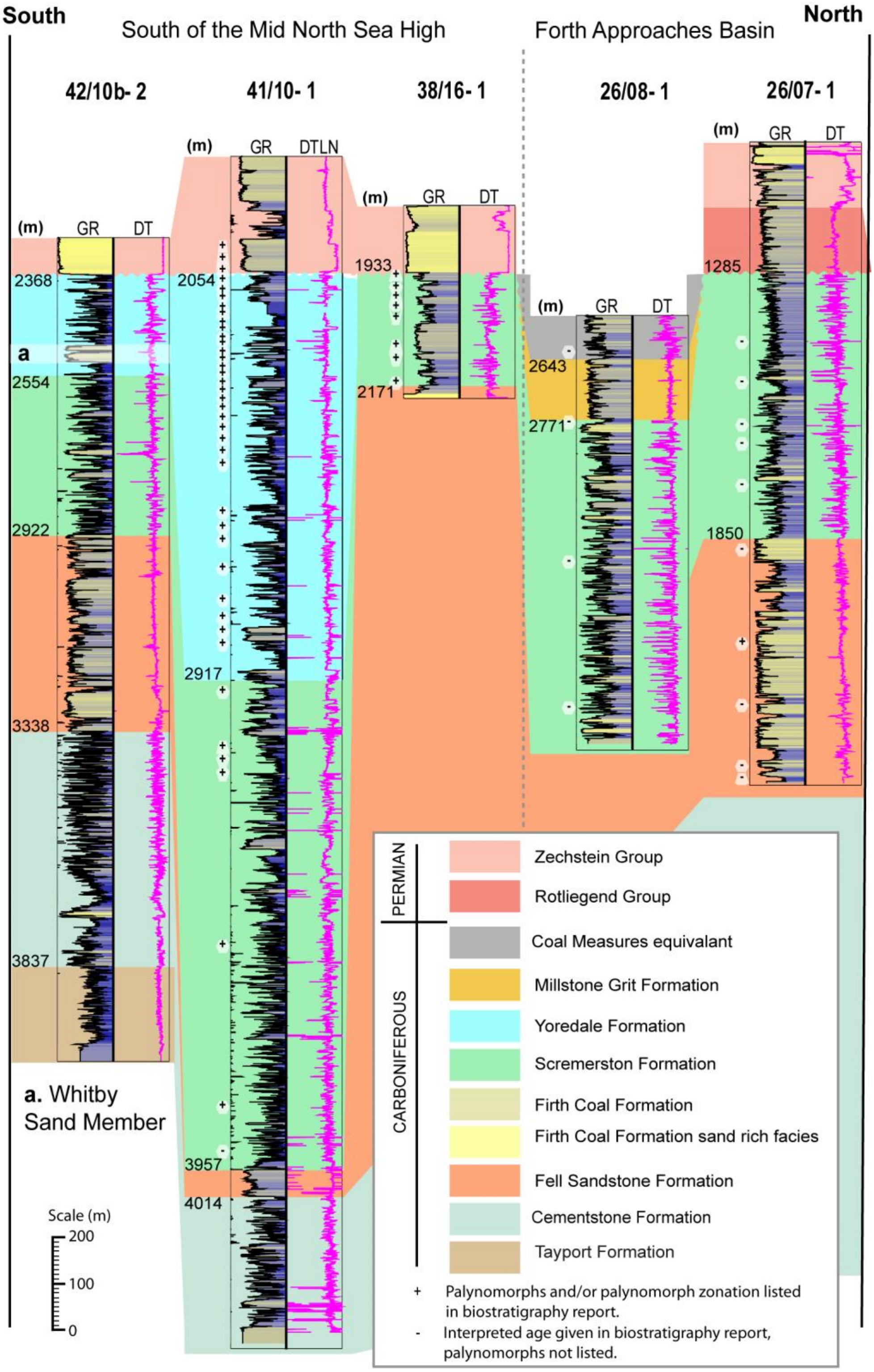

Fig. 6. Correlation panel of Carboniferous strata from south of the Mid North Sea High, through the Forth Approaches The position of the Whitby Sandstone Member is marked by ‘a.’. The gamma curve (GR) is scaled from 0-150 API and the sonic curve (DT) is scaled from 140-40 μs ft^{-1}. For biostratigraphic data see Appendix 1. A large scale version of Fig 6 and 7 as a single panel can be found in Supplemental Fig. 1 (Some well curves supplied by CGG)

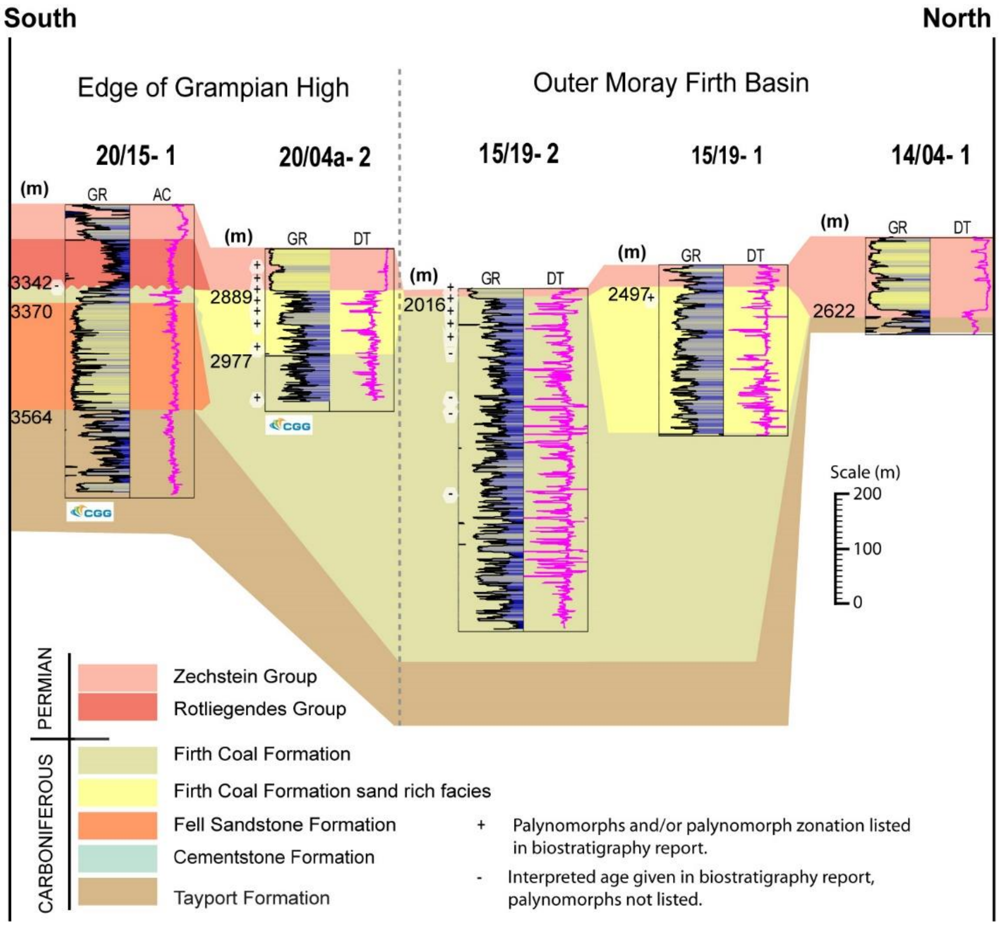

Fig. 7. Correlation panel of Grampian high and Outer Moray Firth Basins. The thickness of Carboniferous strata decreases markedly north of the Forth Approaches when compared to Fig 6. For biostratigraphic data see Appendix 1. A large scale version of Fig 6 and 7 as a single panel can be found in Supplemental Fig. 1. (Well curve data for 20/04a -2 and 20/15-1 supplied by CGG for the 21CXRM Palaeozoic Project results upon which this paper is based)

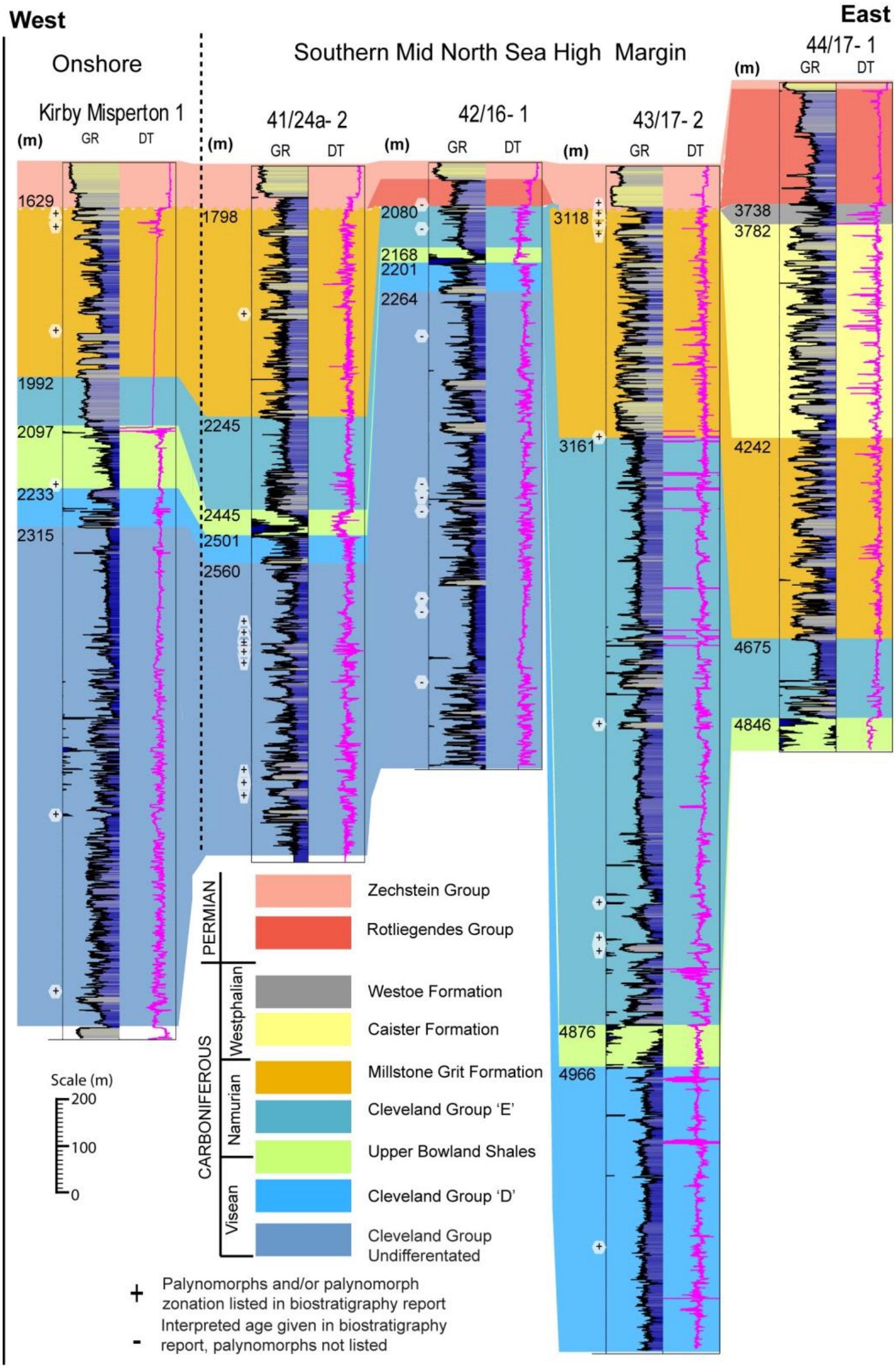

Fig. 8. Correlation panel of Carboniferous strata from west to east across Quadrants 41, 42 and 43, showing the Cleveland Group and Upper Bowland Shales distribution, representative of the basinal mudstone 3 km thick succession. The transition from the Cleveland Group 'E' and the Millstone Grit Formation is diachronous and both were being deposited in different parts of the basin. For

biostratigraphic data see Appendix 1. A large scale version this figure can be found in Supplemental Fig. 2.

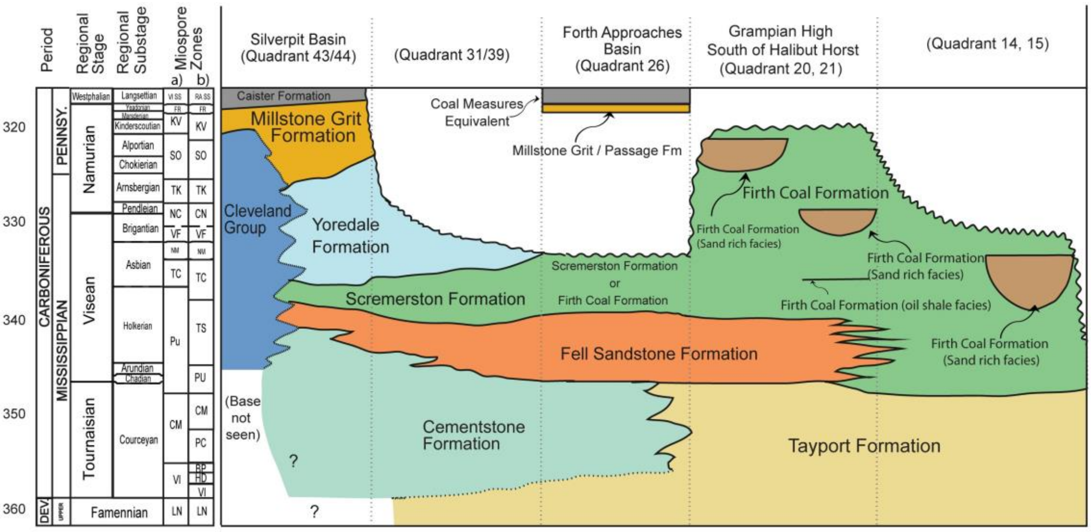

Fig. 9. Stratigraphical relationships of Upper Devonian to Carboniferous strata between the Outer Moray Firth Basins and the Silverpit Basin. Miospore Zone a) is 'former index' and b) is the 'index' as described by Waters *et al.* (2011). Correlation between miospore biozone and global timescale after Davydov *et al.* (2004).

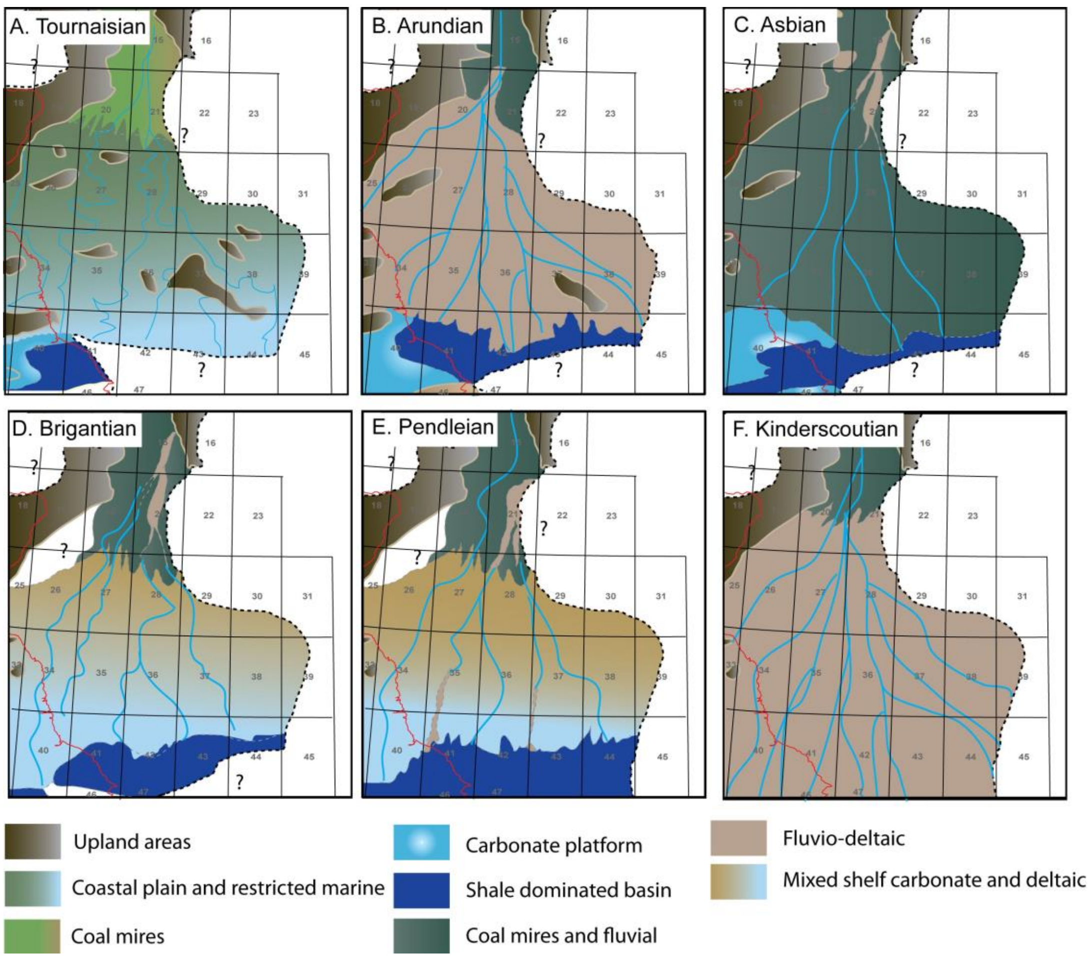

Fig. 10. Schematic evolution model of facies distribution in the North Sea based on well data during the (**a**) Tournaisian (earliest Carboniferous); (**b**) Arundian (early Visean); (**c**) Asbian (late Visean); (**d**) Brigantian (late Visean); (**e**) Pendleian (early Namurian); (**f**) Kinderscoutian (mid Namurian). The dashed line at the eastern margin of each time-slice reflects the extent of the data available for this study (within UK waters).