Articles

Stratigraphic synchronization of the uppermost Devonian and Lower Carboniferous of the Central and Southern North Sea area: palaeoenvironmental and source-rock implications

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Abstract: This contribution addresses the cross-border geology of the Upper Devonian and Lower Carboniferous of the UK, Dutch, Danish, German and Norwegian sectors of the Central and Southern North Sea. Using palynostratigraphic and log analysis, outcrop sections and well stratigraphic sections were tied to the geological timescale. Seven chronostratigraphic units were defined to better visualize lateral and temporal variations. Generalized stratigraphies and facies trends were summarized for 19 areas collectively covering the five national offshore sectors. The results show that two major regional unconformities affected deposition in the area; the Base Visean and the mid-Namurian unconformities. Particularly important phenomena are the development of extensive sandstones of the Fell Sandstone Formation by Arundian–Holkerian times and the development of cyclic delta-plain deposits, comprising both marine limestones and siltstones, as well as coals, by Asbian and Brigantian times. The Asbian marks an isolated phase of accumulation of lacustrine oil shales, in specific tectonic configurations.

Supplementary material: Seven appendices are available, including sedimentary and lithofacies logs (Appendices A and B), details of the biostratigraphic interpretation of outcrop and core sections (Appendices C and D), palaeobotanical affinities of spore and pollen taxa (Appendix E), the stratigraphic interpretations used by, and made in, this study (Appendix F: stratigraphic well database), and a map displaying averaged T_{Max} data for the Visean and Namurian (Appendix G), along with a list of the references used exclusively in the Supplementary material; these appendices are available at https://doi.org/10.6084/m9.figshare.c.8035476

While Upper Carboniferous successions (e.g. Westphalian or Pennsylvanian) have been the main focus of hydrocarbon exploration in the Paleozoic of the North Sea (Cameron 1993; Bruce and Stemmerik 2003; Doornenbal and Stevenson 2010; Kombrink *et al.* 2010; Huis in 't Veld and Den Hartog Jager 2025), older stratigraphic intervals of the Carboniferous System (e.g. 'pre-Westphalian', or Dinantian and Namurian in European terminology) have experienced an increase in interest over the past decades. This was spurred by the discovery of the Breagh Field in the UK offshore of the Southern North Sea (Symonds *et al.* 2015; Grant *et al.* 2020), in which gas is produced from extensive Visean marine–deltaic deposits (Yoredale Formation). In addition, a mainly Namurian deep-water system developed in the southern UK and Dutch North Sea sectors comprises potential source-rock intervals (Gerling *et al.* 1999; Rodriguez *et al.* 2014). These developments led the British Geological Survey (BGS) and industry partners to execute the 21st Century Exploration Roadmap (21CXRM) Palaeozoic Project back to provide regional interpretations of Paleozoic petroleum systems in the UK–North Sea area (Monaghan *et al.* 2017; Kearsey *et al.* 2019). In the meantime, the TNO-Geological Survey of the Netherlands (TNO-GSN) executed the Northern Offshore Project, focusing on Rotliegend and Carboniferous successions of the under-explored northern part of the Dutch offshore (De Bruin *et al.* 2015). As with these two projects, other recently published geological syntheses focus on areas delimited by national borders (Patruno *et al.* 2019; Ter Borgh *et al.* 2019*a*, *b*; Doornenbal *et al.* 2022). These typically provide local constraints, but often lack cross-border considerations and integration of subsurface datasets from North Sea countries. Exceptions are the work of Besly (2019) and Patruno *et al.* (2021). The former provides a retrospective summary of petroleum system elements focusing on the UK and Dutch Southern North Sea. The latter provides a longer-term (Paleozoic–Cenozoic) megasequence framework with a cross-border perspective. A general lack of detailed cross-border integration is illustrated by a synthesis of available published stratigraphic information for the region produced by collating several lithostratigraphic national nomenclatures (Fig. 1). This displays a notable lack of alignment and a great variability in the level of detail. The latter is partly caused by a general scarcity of data for the Upper Devonian and Lower Carboniferous, especially in the Norwegian, Danish and German sectors of the North Sea. Therefore, a more systematic evaluation of the limited available information, combined with an integration of British and Dutch datasets and knowledge, would allow for a better synchronization of the stratigraphy across the Central and Southern North Sea areas.

These developments collectively led the TNO-GSN and BGS to join forces and establish an industry-funded Joint Industry Project ('Paleo-Five Project') aimed at establishing a cross-border understanding of the tectonostratigraphic evolution of the Late Devonian–Early Carboniferous (up to Namurian) of the British, Dutch, German, Danish and Norwegian sectors of the Central and Southern North Sea (Fig. 2). The main results and insights arising from the Paleo-Five Project are distilled here and in the companion publication (Bouroullec *et al.* 2025*b*, this volume).

This paper focuses specifically on the construction of a cross-border chronostratigraphic framework based on the integration of new and legacy palynological data, well-log interpretations, and sedimentological core description. This framework is subsequently used to assess lithofacies trends (based on outcrop and

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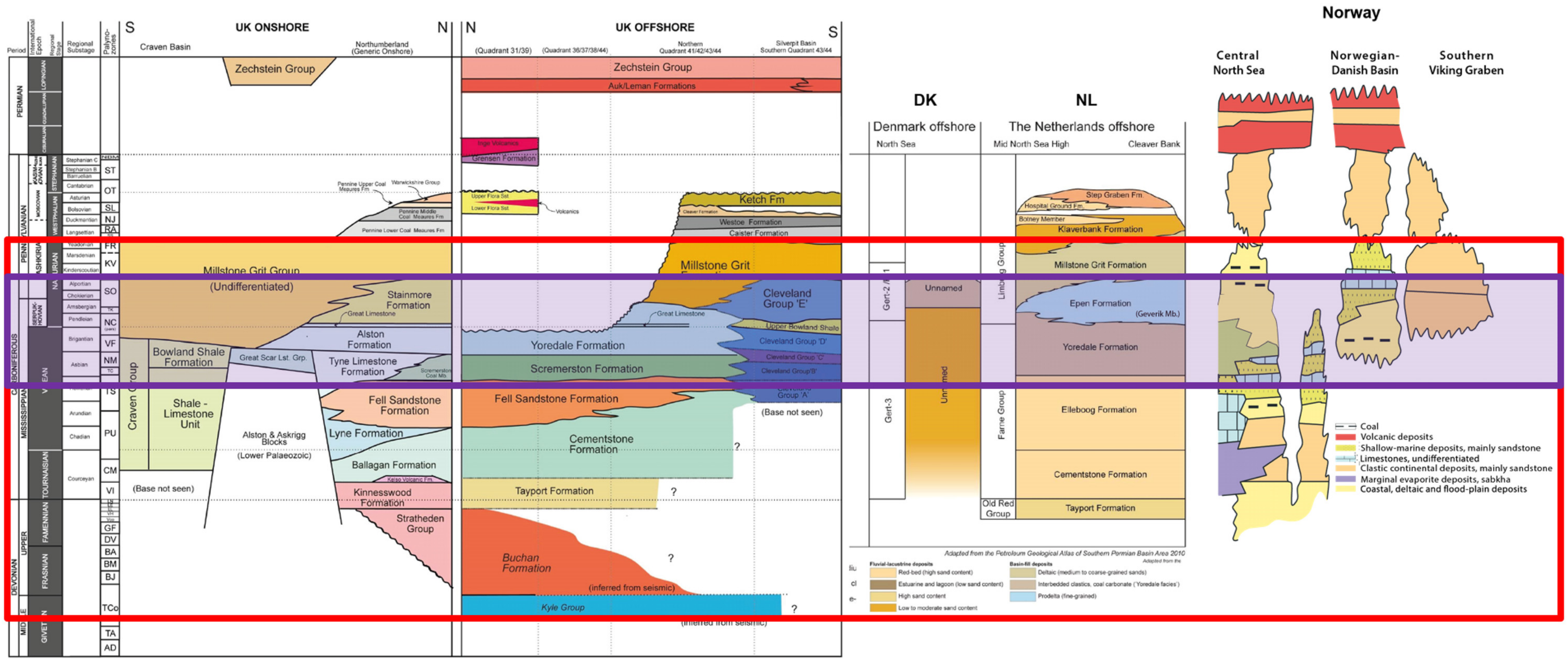

Fig. 1. Stratigraphic schemes for the Carboniferous in the UK, Denmark, The Netherlands and Norway. The stratigraphic scope of the Paleo-Five Project is outlined in the red box. Most pre-Westphalian source rocks occur in the purple box, which represents the focus of palynological and organic-geochemical analyses carried out for this study. The stratigraphic schemes are derived from (left to right): the 21CXRM Project (BGS: Kearsey *et al.* 2019), the SPBA Atlas (Denmark and the Netherlands: Doornenbal and Stevenson 2010) and the 2014 Norwegian Petroleum Directorate (NPD) lithostratigraphic chart for the North Sea (NPD 2014). Note that no German scheme has been published for the Devono-Carboniferous.

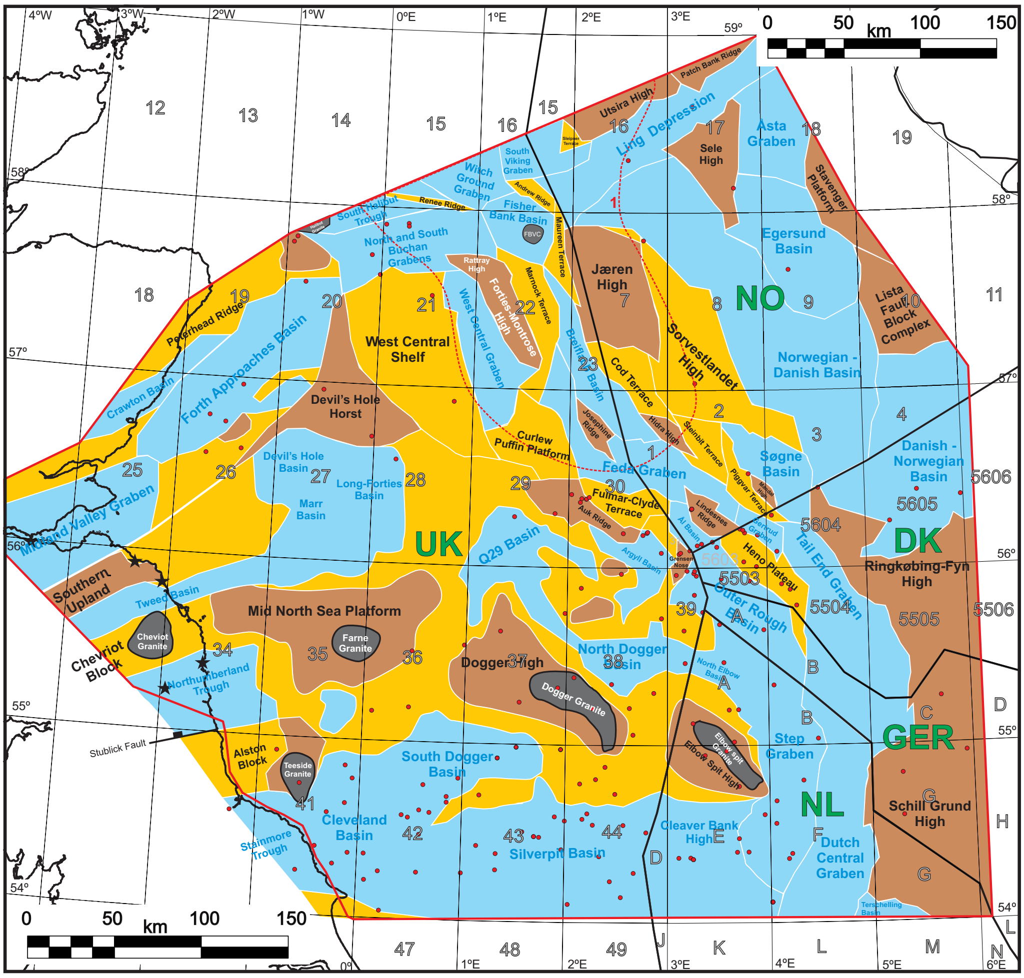

Fig. 2. Main Paleozoic and Mesozoic structural provinces in the study area. Wells with Carboniferous or older penetration are indicated as red dots (see Fig. 6 for their names). The outcrop locations are indicated by stars. Note that some of the defined structural elements are not exclusively Paleozoic structures but rather consist of a mix of Paleozoic and Mesozoic structures, especially in proximity to the Mesozoic Central Graben. Some minor changes were made to the shape and extent of some elements based on results of this study and to allow a better fit between nationally established structural elements. Dark grey polygons represent plutonic intrusions; light brown polygons represent structural highs; orange polygons represent platforms and terraces; blue polygons represent basins. FBVC, Fisher Bank Volcanic Centre. Zone 1, highlighted by the dashed red polygon, corresponds to the area uplifted during the Mid-Jurassic doming and where the Intra-Aalenian Unconformity eroded down to Pre-Permian stratigraphy. Source: after Bouroullec *et al.* (2025*b*); the structural elements displayed are based on published information from TNO-GDN, BGS, NPD, the Millennium Atlas (Evans *et al.* 2003), and the Southern Permian Atlas (Doornenbal and Stevenson 2010).

core logging), palaeoenvironmental interpretations (supported by new quantitative palynological analysis), source-rock quality (through new and legacy Rock-Eval analysis) and, finally, stratigraphic distribution across the extensive study area. The companion article by Bouroullec *et al.* (2025*b*) provides a new regional-scale tectonostratigraphic and structural model that was derived through the integration of well-, seismic- and outcrop-based interpretations.

This work examines the nearly complete stratigraphic succession comprising Upper Devonian–Namurian lithostratigraphic units exposed along the coast of Northumberland and the Scottish Borders area in the UK (Figs 1 & 2). Five main outcrop sections were selected for sedimentological and palynological analysis and source-rock evaluation (Table 1). More than 1600 m of stratigraphy were measured, providing an integrated insight into the depositional palaeoenvironmental evolution and depositional trends, stacking patterns, reservoir characteristics, and source-rock potential of specific facies or facies associations. In the offshore part of the study area (Fig. 2), a total of 181 wells penetrating pre-Westphalian successions (i.e. Lower Carboniferous and/or older strata) were evaluated. Wireline-log, biostratigraphic and geochemical legacy data were combined with newly acquired stratigraphic, biostratigraphic and geochemical data from cores and cuttings. For reasons of space, detailed lithology and lithofacies, and palynology-based palaeoenvironmental and (bio)stratigraphic interpretations are provided in the Supplementary material, whereas the main body of this paper focuses on integrative results.

Starting from the integration of legacy data and results of the 21CXRM Palaeozoic Project (Kearsey *et al.* 2019), revised chrono- and lithostratigraphic interpretations are provided for onshore and offshore British sectors and offshore sectors of The Netherlands, Germany, Denmark and Norway within the project's study area (Fig. 2). Together with the well-dated reference framework from the coastal British outcrops, these new interpretations aim to lay the foundation for a new cross-border stratigraphic synchronization. The resulting updated framework is subdivided into seven chronostratigraphic intervals (units 1–7), for each of which idealized stratigraphic infills covering 19 geographical areas are described, based mainly on assessments of well data. These seven chronostratigraphic units are either unconformity-bounded or reflect major synchronous changes in depositional regimes. Subsequently, for each chronostratigraphic interval, regional palaeoenvironmental reconstructions and source-rock evaluations are presented through time and space. The goal of this work is to

Table 1. Outcrop location list, displaying the GPS coordinates of the outcrop sections, the recorded stratigraphic thickness and the approximate chronostratigraphic position of the respective measured sections

Locality	GPS Coordinates (starting and ending points, in degrees and decimal minutes)	Measured thickness (m)	Approximate chronostratigraphy
Pease Bay/Cove	55.934760 N, 2.337504 W 55.939382 N, 2.346728 W	340	Famennian–Tournaisian–Visean
Burnmouth	55.842294 N, 2.069171 W 55.835919 N, 2.055322 W	540	Famennian-Tournaisian
Spittal	55.751673 N, 1.983691 W 55.734287 N, 1.961506 W	365	Visean
Cocklawburn 1	55.731415 N, 1.957101 W	5	Visean
Cocklawburn 2	55.436770 N, 1.570160 W	4	Visean
Cocklawburn 3	55.436470 N, 1.569580 W	3	Visean
Cocklawburn 4	55.726734 N, 1.947259 W	5	Visean
Cocklawburn 5	55.726212 N, 1.946615 W	25	Visean
Cocklawburn 6	55.724810 N, 1.944488 W 55.724483 N, 1.944098 W	15	Visean
Queensferry	55.991640 N, 3.377268 W 55.990876 N, 3.383549 W	67	Visean
Howick 1	55.455690 N, 1.591996 W 55.460833 N, 1.591444 W	60	Visean
Howick 2	55.454727 N, 1.592518 W 55.450508 N, 1.587476 W	50	Namurian
Howick 3	55.446519 N, 1.587530 W 55.445695 N, 1.585461 W	25	Namurian
Howick 4	55.446640 N, 1.587329 W	4	Namurian
Howick 5	55.444781 N, 1.589733 W 55.444429 N, 1.588715 W	15	Namurian
Howick 6	55.439932 N, 1.593315 W 55.438108 N, 1.591208 W	35	Namurian
Howick 7	55.436394 N, 1.588842 W 55.435177 N, 1.586804 W	30	Namurian

provide a reference stratigraphic framework and knowledge base for the Late Devonian–Early Carboniferous stratigraphy of the Central and Southern North Sea, forming a conceptual foundation for future research efforts into the geoenergy resources of this economically important west European region.

Regional setting

The study area (Fig. 2) comprises the southern part of the Central North Sea (CNS) and a large part of the Southern North Sea (SNS), collating data from coastal outcrops in NE England (Northumberland) and SE Scotland (Scottish Borders) with well data from the UK, Norwegian, Danish, Dutch and German sectors.

From the Middle Devonian to Early Carboniferous times the study area was located at southern tropical latitudes, in proximity to the southwestern margin of the Laurasia supercontinent (Domeier and Torsvik 2014). By the early Paleozoic (Ordovician–earliest Devonian times), the southern margin of Laurasia was affected by convergence of Laurasia and Baltica (the Caledonian Orogeny: Strachan 2012; Domeier and Torsvik 2014), leading to uplift and erosion of Precambrian and lower Paleozoic strata. These would successively source terrigenous debris for Late Devonian–Carboniferous stratigraphic units that presently overlie the basal Caledonian Unconformity in the SNS (Fraser and Gawthorpe 2003). Several NE–SW-orientated structural lineaments and associations active during the Caledonian orogenic phase formed a template that would be reactivated during the Early Carboniferous formation of local extensional and transtensional (sub)basins northwards of the suture zone (Leeder 1982; Pharaoh 1999; Fraser and Gawthorpe 2003). Post-orogenic, Late Devonian–Early Carboniferous extension has been recognized from structural and stratigraphic evidence in various sectors of northwestern Europe (e.g. Fossen and Dunlap 1998; Oncken *et al.* 2000; Fraser and Gawthorpe 2003), and resulted in a series of WNW–ESE-trending, fault-bounded half-graben in the SNS. Several fault-bounded, locally interconnected, rapidly subsiding basins with a main east–west trend (e.g. the Midland Valley of Scotland, the Northumberland Trough, and the Solway, Tweed and Cleveland basins: Fig. 2) were separated by basement highs locally cored by magmatic intrusions (Monaghan and Parrish 2006). These highs host mostly clastic continental to shallow-marine deposits. Strong tectonic control in this early phase of depositional history was followed, from Visean times onwards, by progressively reduced deformation rates of the

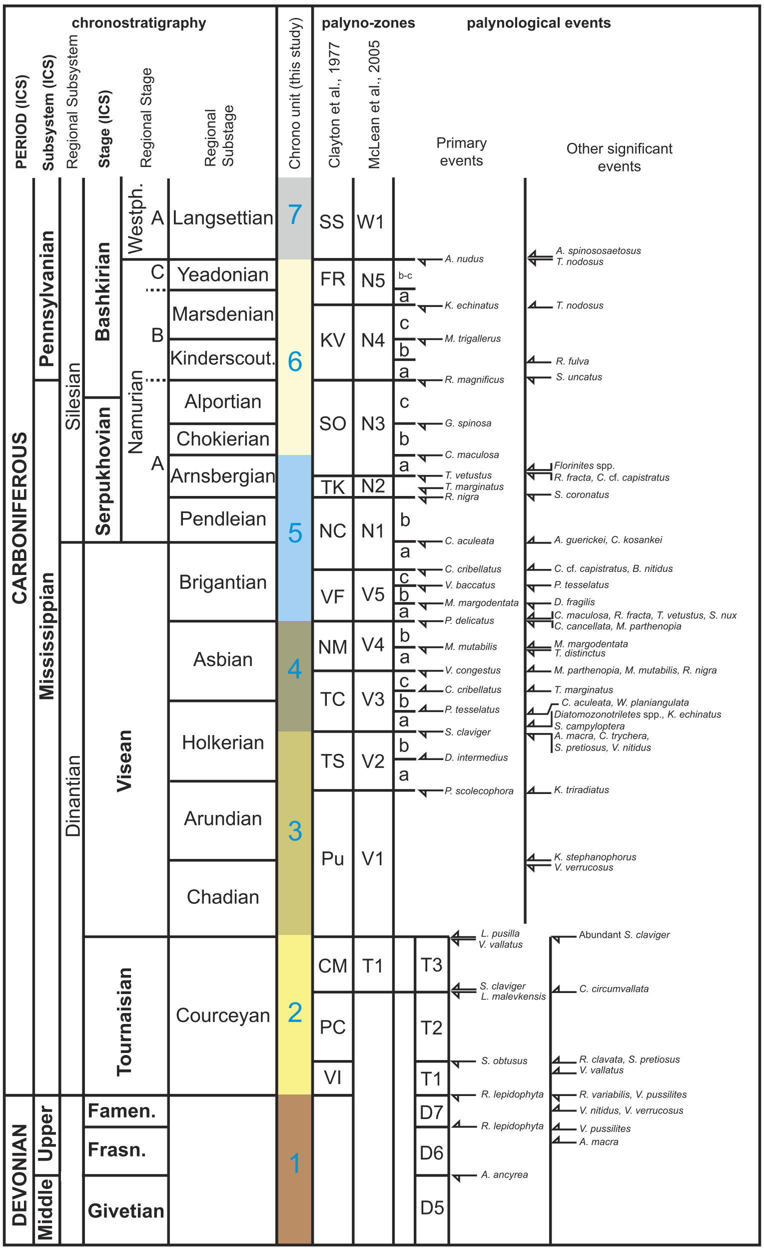

Fig. 3. Stratigraphic comparison charts. The chart shows the global (International Committee on Stratigraphy (ICS)) chronostratigraphic nomenclature v. the nomenclature that is used regionally in the UK and North Sea. The chronostratigraphic units (1–7) are indicated by colours. On the right-hand side of this chart, the palynological zonations of Clayton *et al.* (1977) and McLean *et al.* (2005) are indicated. For the Tournaisian and Devonian the D5-T3 zonation is after the unpublished report of McLean (2012). The 'other significant events' are a somewhat subjective appreciation of the information provided by these authors seen in the light of our own observations during this project. Kinderscout., Kinderscoutian; Famen., Famennian; Frasn., Frasnian.

principal active lineaments and by more diffuse, regional-scale post-rift subsidence, leading to patterns of sedimentation being controlled mostly by glacioeustatically driven base-level changes by about mid-Carboniferous (Namurian) times (Wright and Vanstone 2001; Montañez and Poulsen 2013). Ongoing northward convergence between Gondwana and Laurasia culminated in the Variscan Orogeny, terminating the dominantly extensional regime with inversion of the transversely orientated NE–SW-trending basins. Northward-orientated subduction and accretion of the Variscan fold-and-thrust belt south of the study area gradually developed a Westphalian peripheral foreland basin and further tectonic inversion and deformation of Early Carboniferous basins and their hosted successions, ultimately resulting in the Base Permian Unconformity (BPU: Kombrink *et al.* 2010; Bouroullec *et al.* 2025*b*, fig. 13). During the Permian and Mesozoic the North Sea region was mostly affected by intra-plate deformation, progressively leading to Permo-Triassic and Late Jurassic rifting phases that contributed to the present-day configuration of three principal, interconnected extensional depocentres (the Moray Firth, Viking Graben and Central Graben: Zanella *et al.* 2003; Bouroullec *et al.* 2018; Patruno *et al.* 2021), filled mostly by shallow- to deep-marine, clastic-dominated successions. The plate and basin evolution of this part of the North Sea have been the subject of many studies and publications, and are summarized in Bouroullec *et al.* (2025*b*).

Long-term palaeoclimatic trends for the middle Paleozoic of the study area saw a gradual shift from a semi-arid setting during the Middle and Late Devonian to increasingly humid climate, possibly with marked seasonality, from the earliest Carboniferous (Tournaisian) into the Late Carboniferous. This transition can be largely attributed to changing palaeolatitudinal positions during northward drift of the Laurasian margin (Cocks and Torsvik 2006). A Late Devonian position within the semi-arid subtropical latitudinal belt would have been followed by progressive repositioning within the subequatorial humid belt by early Carboniferous times (Cocks and Torsvik 2006). Much of the evidence on Devonian aridity is based on successions from East Greenland, regionally contiguous to the study area at the time (e.g. Astin *et al.* 2010). Insights into Early Carboniferous conditions are provided by geochemical proxies, and palaeopedological and palaeobotanical analyses of British successions (Vanstone 1991; Falcon-Lang 1999; Kearsey *et al.* 2016; Millward *et al.* 2018).

It has been hypothesized that towards the end of the Early Carboniferous (late Visean), enhanced seasonality would have developed due to progressive convergence of continental masses into the Pangaean assemblage and the initiation of continental glaciation in the southern hemisphere, during coeval onset of the late Paleozoic icehouse (by Asbian–Brigantian times: e.g. see Montañez and Poulsen 2013).

Chronostratigraphic terminology

In northwestern Europe, numerous regional chronostratigraphic terminologies for the Late Devonian and Early Carboniferous are used, particularly on the Stage and Substage levels. The 'early' Carboniferous, according to the International Commission on Stratigraphy (ICS: Gradstein and Ogg 2020) is to be referred to as the Mississippian Series (Fig. 3). The Mississippian consists of three subseries (Early, Middle and Late) that correspond to the Tournaisian, Visean and Serpukhovian stages, respectively. Historically, the Carboniferous succession of western Europe was subdivided into two series: the lower part, dominated by marine facies, was called the Dinantian; and the upper part, dominated by terrestrial facies, was called the Silesian. The Dinantian was divided into two stages, the Tournaisian and Visean. The Silesian was divided into the Namurian, Westphalian and Stephanian. This traditional scheme became obsolete with the definition of the mid-Carboniferous boundary, which is a boundary within the Silesian, corresponding roughly to the Namurian A–B boundary in traditional nomenclature (Dusar 2006; Wagner and Winkler Prins 2016). This also means that the Mississippian and Dinantian stages are not fully equivalent (Fig. 3). The UK subdivision on the Substage level was formally proposed by George *et al.* (1976) and Ramsbottom *et al.* (1978) with a later update by Waters *et al.* (2011). For the Dinantian, these are, in ascending order: the Courceyan (Tournaisian), the Chadian and Arundian (early Visean), the Holkerian (middle Visean), and the Asbian and Brigantian (late Visean). The lower two substages of the Namurian (Pendleian and Arnsbergian) correspond to the Serphukhovian ICS stage. Because most reference sections, legacy materials and preceding studies utilize the UK-based stage definitions, we here adhere to the latter.

Database and methodology

Outcrop-based sedimentary logs and sampling

Outcrop sections were logged and sampled, collectively covering samples from the Upper Devonian Greenheugh Formation (Stratheden Group) and Kinnesswood Formation (Inverclyde Group) to the base of the Namurian Millstone Grit Group. Most selected exposures are cliff faces and foreshores accessible along the coast between the villages of Longhoughton and Howick in NE England (*c.* 50 km north of Newcastle) to the locality of Pease Bay in SE Scotland (*c.* 50 km SE of Edinburgh: Fig. 2). Stratigraphic sections were measured at centimetric resolution following conventional sedimentological practice; sedimentary facies were defined by lithology, bedding geometry and contacts, primary or secondary sedimentary structures, ichnological signature, and fossil content (where applicable). The same approach was applied to the logging of offshore cores, except for the verification of bedding geometries. Where possible, stratigraphic and sedimentological observations were preferentially carried out on well-exposed, clear-cut sections along coastal cliffs. Due to the low-angle to subhorizontal bedding attitude of several stratigraphic intervals, logging was frequently carried out on wave-cut platforms and exposures in the foreshore; in these geometrically unfavourable settings, a Jacob's staff was employed to minimize errors in the measurement of stratigraphic thickness. Parts of the studied successions have previously been described by other authors (Gardiner 1983; Kearsey *et al.* 2016; Booth *et al.* 2020). Note that the lower 176 m of the Spittal measured section (see Supplementary Appendix A) were derived from one of the excellent quality measured sections of Gardiner (1983), with few modifications. Systematic analyses of stratigraphic architectural elements were not an objective of this study; however, numerous outcrop panoramas were obtained by means of a drone to construct photopanels used for stratigraphic correlations. These aerial images were of great value for identifying angular unconformities, bed thickness variation and channels along the dipping beds cropping out along the foreshore and exposed at low tides. Most outcrop samples are derived from the above-mentioned coastal measured sections, but other locations were also sampled to target specific lithostratigraphic units.

Well database and sampling

The well database contains 181 wells penetrating Carboniferous or older strata in the Norwegian, Danish, German, Dutch and UK sectors of the Central and Southern North Sea (see Fig. 2). Biostratigraphic data from 64 wells were used for correlation (Table 2). For many wells, legacy biostratigraphic and lithostratigraphic data are available via open sources such as NLOG (Dutch wells: https://www.nlog.nl/en/boreholes), the Norwegian Offshore Directorate Fact Pages (Norwegian wells: https://factpages.sodir.no/en/wellbore), the GEUS website (Danish wells: https://data.geus.dk/geusmap/), and the 21CXRM Palaeozoic Projects (https://www.nstauthority.co.uk/regulatory-information/exploration-and-production/exploration/ukcs-regional-projects/) and the North Sea Transition Authority (NSTA) website (https://itportal.nstauthority.co.uk/information/well_data/bgs_tops/geological_tops/geological_tops.htm). New material was also collected for the present research, with 168 samples from outcrop and offshore core sections sampled for palynological analysis. Organic characterization using total organic carbon (TOC) content and Rock-Eval pyrolysis was carried out on 395 and 287 samples, respectively (Table 3).

Palynology and organofacies analysis

The processing of outcrop and core samples for the palynological analyses was performed by Malcolm Jones (Palynology Laboratory Services Ltd). Rocks were first crushed and treated with hydrochloric acid to remove the carbonate fraction. A second step involved treatment with hydrofluoric acid to dissolve the silicate fraction and free any acid-resistant organic matter from its mineral matrix. After neutralization with water, the solution was sieved over a 10 µm mesh to concentrate the organic particles. Ultimately, the remaining organic fraction was fixed on the slide using a UV-cured permanent mounting medium.

All palynological preparations were studied with a microscope under transmitted light using ×500–×787 magnification. Two separate analytical suites were carried out: one focusing on organofacies analysis and the other on quantification of the palynological association. For the former, phytoclasts, amorphous organic matter (AOM) particles and discernible palynomorphs were quantified. The second suite focused on quantification of the palynomorph associations and the pollen and spore assemblages specifically. The pollen and spore assemblages are interpreted in two ways. For age interpretation, they are displayed in distribution charts showing the stratigraphic ranges of different species for each well or outcrop section (Supplementary Appendix C). In order to obtain an understanding of the development of vegetation types in the study area, the sporomorph taxa were grouped according to their parent-plant type. This classification is based on Davies and

Table 2. Well list showing all wells for which core logging, sampling and either new or legacy biostratigraphic information is available

Country/sector	Well	Core logging and sampling	Biostratigraphic information available
Denmark (DK)	Gert-2	Yes	This study
The Netherlands (NL)	A16-01	Yes	This study
The Netherlands (NL)	E02-01		This study, legacy
The Netherlands (NL)	E02-02		This study, legacy
The Netherlands (NL)	E06-01	Yes	This study
Norway (N)	2/7-26s	Yes	This study but not diagnostic
Norway (N)	2/10-1s		Legacy
Norway (N)	2/11-8		Legacy
Norway (N)	2/11-9	Yes	This study
Norway (N)	9/4-5		This study (cuttings)
UK	14/19-2		Legacy
UK	15/11-1		Legacy
UK	15/18-2		Legacy
UK	20/15-2	Yes	This study, legacy
UK	21/02-1		No
UK	21/13b-1a		Legacy
UK	26/07-1		Legacy
UK	26/08-1		Legacy
UK	31/27-1		Legacy
UK	36/13-1		Legacy
UK	36/15-1		Legacy
UK	36/23-1		Legacy
UK	37/10-1		Legacy
UK	37/25-1		Legacy
UK	38/01-1		Legacy
UK	38/03-1		Legacy
UK	38/16-01	Yes	This study, legacy
UK	38/18-1		Legacy
UK	38/22-1		Legacy
UK	39/07-1		Legacy
UK	41/01-1	Yes	This study, legacy
UK	41/05-1		Legacy
UK	41/10-1		Legacy
UK	41/14-1		Legacy
UK	41/15-1	Yes	This study, legacy
UK	41/18-1		Legacy
UK	41/24-a2		Legacy
UK	42/09-1	Yes	This study, legacy
UK	42/10b-2	Yes	This study, legacy
UK	42/13-1		Legacy
UK	42/13-2	Yes	This study, legacy
UK	42/13-3		Legacy
UK	42/13-4		Legacy

(*Continued*)

Table 2. *Continued*

Country/sector	Well	Core logging and sampling	Biostratigraphic information available
UK	42/15a-2	Yes	This study, legacy
UK	42/18-2		Legacy
UK	42/22-1		Legacy
UK	42/23-1		Legacy
UK	42/27a-1	Yes	This study, legacy
UK	43/02-1	Yes	This study, legacy
UK	43/03-1		Legacy
UK	43/06-1		Legacy
UK	43/16-2		Legacy
UK	43/17-2		Legacy
UK	43/19-2	Yes	This study, legacy
UK	43/20-b-2		Legacy
UK	43/21-2		Legacy
UK	43/22-1		Legacy
UK	44/02-1	Yes	This study, legacy
UK	44/12-1		Legacy
UK	44/13-1		Legacy
UK	44/17-1		Legacy
UK	44/19-3		Legacy
UK	44/21b-8		Legacy
UK	44/28-3		Legacy

McLean (1996), Lindstrom (2003) and Jasper *et al.* (2010), and precise assignments are listed in Supplementary Appendix E. The following parent-plant types with presumed ecological significance were established: arborescent lycopsids, non-arborescent lycopsids, tree ferns and cycads, ferns, sphenopsids, cordaites, and a group of spores with unknown parent-plant relationship. Arborescent lycopsids, tree ferns and cycads, sphenopsids, and cordaites could reach tree size.

The Carboniferous Period has drawn the attention of palynologists since the 1960s, because of the abundance of pollen and spores. Over the years, many palynological zonations have been defined, many of which focused on coal-producing areas in the UK, The Netherlands, Belgium and Germany. One of the first, most complete and stable zonation schemes was that of Clayton *et al.* (1977), relying on an array of reference sections in the UK, Belgium, France and Germany. Most of the zones established in that paper are named after two First Occurrence Datums (FODs) at the base of the zone. For example, the VF zone is named after the FODs of *Tripartites vetustus* and *Rotaspora fracta* at the base of the zone. Because FODs are not always practical to use, especially when dealing with cuttings samples in exploration wells, the zonation has been improved and refined many times for use in the oil and gas industry. The most important updated zonation in this respect is that of McLean *et al.* (2005), who managed to reach a much higher resolution by defining subzones and who also improved on the implementation of Last Occurrence Datums (LODs) into the zonation. The latter zonation uses numbering based on the stage names, rather than species names. For example, V5 refers to the fifth zone in the Visean. To provide some clarity in the multitude of events used in numerous zonations, Figure 3 presents an overview of the primary events: that is, those that define bases and tops of zones, and the most significant taxa that have extinctions or originations, as mentioned by Clayton *et al.* (1977) and McLean *et al.* (2005).

Organic geochemistry

The samples for organic geochemical source-rock characterization, involving Rock-Eval pyrolysis and TOC content analyses, were analysed by Applied Petroleum Technology (APT) in Norway and at the BGS laboratory in Keyworth, UK.

At APT, TOC content measurements were carried out using a Leco SC-632 instrument. Diluted HCl was added to the crushed rock sample to remove carbonate. The sample was then introduced into the Leco combustion oven, and the amount of carbon in the sample was measured as carbon dioxide using an infra-red (IR) detector. For organic pyrolysis, a Rock-Eval 6 instrument was used employing the following temperature programme for pyrolysis: initial oven programme of 300°C for 3 min, heating to 650°C with a heating rate of 25°C min^{-1}. The Jet-Rock 1 standard was run as every 10th sample and checked against the acceptable range given in the Norwegian Industry Guide to Organic Geochemical Analyses (NIGOGA: https://www.sodir.no/globalassets/1-sodir/regelverk/forskrifter/en/geochemical-analysis.pdf).

At the BGS, a Vinci Technologies Rock-Eval 6 standard instrument was used for the Rock-Eval pyrolysis. The temperature programme used an initial oven temperature of 300°C for 3 min and then the sample was heated from 300 to 650°C at a rate of 25°C min^{-1} in an N_2 atmosphere. The oxidation stage was achieved by heating the sample at 300°C for 1 min, then raising the

Table 3. Number of samples taken from respective outcrop and/or core sections for palynological, total organic carbon (TOC) content and Rock-Eval analysis

Country	Well/ Outcrop	Palynology	TOC content	Rock-Eval
Denmark (DK)	Gert-02	28	14	
Norway (N)	2/11-9	13	Legacy	Legacy
Norway (N)	2/7-26S	5		
The Netherlands (NL)	A16-01	5	6	1
The Netherlands (NL)	E06-01	10	9	1
UK	20/15-2	15	14	6
UK	38/16-1	3	3	1
UK	41/01-1	15	26	15
UK	41/15-1	10	35	21
UK	42/09-1	6	18	5
UK	42/10b-2	10	33	12
UK	42/13-2	8	14	6
UK	42/15a-2	13	44	18
UK	42/27a-1	3	8	1
UK	43/02-1	13	28	10
UK	43/19-2	10	21	6
UK	44/02-1	3	Legacy	Legacy
UK	Howick	23	79	79
UK	Pease Bay	18	51	51
UK	Queensferry	26	27	27
UK	Spittal	35	72	72
Total		**168**	**395**	**287**

temperature from 300 to 850°C at a rate of 20°C min^{-1} and then holding it at 850°C for 5 min. Hydrocarbons released during the two-stage pyrolysis were measured using a flame ionization detector (FID), and carbon monoxide (CO) and carbon dioxide (CO_2) were measured using an IR cell20.

During the pyrolysis heating programme, the free hydrocarbons present in the sample are recorded in the S1 peak in mgHC g^{-1} rock, the hydrocarbons generated during the pyrolysis are recorded in the S2 peak in mgHC g^{-1} rock and the released CO_2 during the final breakdown of the kerogen as the S3 peak in mgCO_2 g^{-1} rock. The combined area under the curve of the S1 and S2 peaks is a measure of the total amount of remaining hydrocarbons that can be generated from the sample.

Biostratigraphy

This section lays the foundation for the stratigraphic synchronization of the 'five nations' area. As a first step, a biostratigraphic interpretation of sampled outcrop sections in Northumberland and the Scottish Borders was established by collating new palynological data and published records (Supplementary Appendix C). This resulted in a chronostratigraphically well-constrained outcrop analogue composite section (Fig. 4). Subsequently, all palynological age dates arising from the investigated core sections were synchronized to arrive at an overview of sedimentological, palynological and organic geochemical data through time (Supplementary Appendix D). Lastly, a cross-border applicable stratigraphic scheme was constructed based on a combination of new and legacy data. To this end, seven chronostratigraphic intervals were defined, which are used throughout this contribution: viz. Unit 1 (Late Devonian), Unit 2 (Tournaisian), Unit 3 (early Visean), Unit 4 (middle Visean), Unit 5 (late Visean–early Namurian), Unit 6 (late Namurian) and Unit 7 (Westphalian).

Biostratigraphic correlation of outcrop sections and offshore core sections

The Cove–Pease Bay, Spittal and Howick sections were analysed palynologically. Recent legacy data are available for the Burnmouth (Marshall *et al.* 2019; Reeves 2019), Spittal and the Cocklawburn sections (both in Ingrams *et al.* 2020). These data were used to provide biostratigraphic breakdowns and additional correlation constraints. For a detailed description of the biostratigraphic considerations, palynological range charts, and detailed lithological and lithofacies information from measured sections, the reader is referred to Supplementary Appendix C. Collectively, these results were used to guide the stratigraphic correlations, as depicted in Figures 4 & 5. This implies that along the Northumberland and Scottish Border coast, we were able to stratigraphically measure and sample most of the Tournaisian–Namurian. The lower part of the Visean (Chadian–early Holkerian) was not sampled, except for the base of the Fell Sandstone at Burnmouth. The section at Queensferry is not part of the Northumberland coastal transect and is not depicted in Figure 4. The derived age for this sequence of lacustrine oil shales is late Asbian (Zone V4a of McLean *et al.* 2005). As further delineated in Supplementary Appendix D, a large majority of the offshore core sections consists of upper Asbian and Brigantian deposits.

Stratigraphic synthesis

In addition to measured outcrop sections, other data types were used for the stratigraphic correlation. Wireline-log patterns and electrofacies were used in combination with biostratigraphic and sedimentological information from legacy reports from 141 wells located across the study area. These provide an overview of the stratigraphic development and depositional facies (see also Bouroullec *et al.* 2025*b*). Existing lithostratigraphic interpretations from the BGS 21CXRM Palaeozoic Project and the GSN lithostratigraphic database have guided these assignments, but have been checked for consistency based on legacy biostratigraphic data and petrophysical wireline-log character (see the well section panels in the supplementary appendices A–D of Bouroullec *et al.* 2025*b*); where possible, new biostratigraphic analyses or log correlations were used. This combined and extensive approach resulted in a synthesis of 19 stratigraphic charts constructed for specific parts of the study area (Figs 6 & 7). Each of these 19 areas, and their representative wells, present a relatively consistent stratigraphic succession that can be used as an anchor, combined with neighbouring regions and expanded to build the regional cross-border stratigraphic synchronization (Fig. 7).

For the sake of clarity and consistency, we elected to describe the stratigraphy along the lines of seven chronostratigraphic intervals. This implies that for each 'area', a range of reported ages led to a respective assignment. This allows consistent mapping of time intervals across the study area and for coeval formations to be grouped (e.g. part of the Firth Coal Formation is coeval with the Yoredale Formation and the informal Cleveland group, *sensu* Kearsey *et al.* 2015, 2019) across multiple structural provinces and

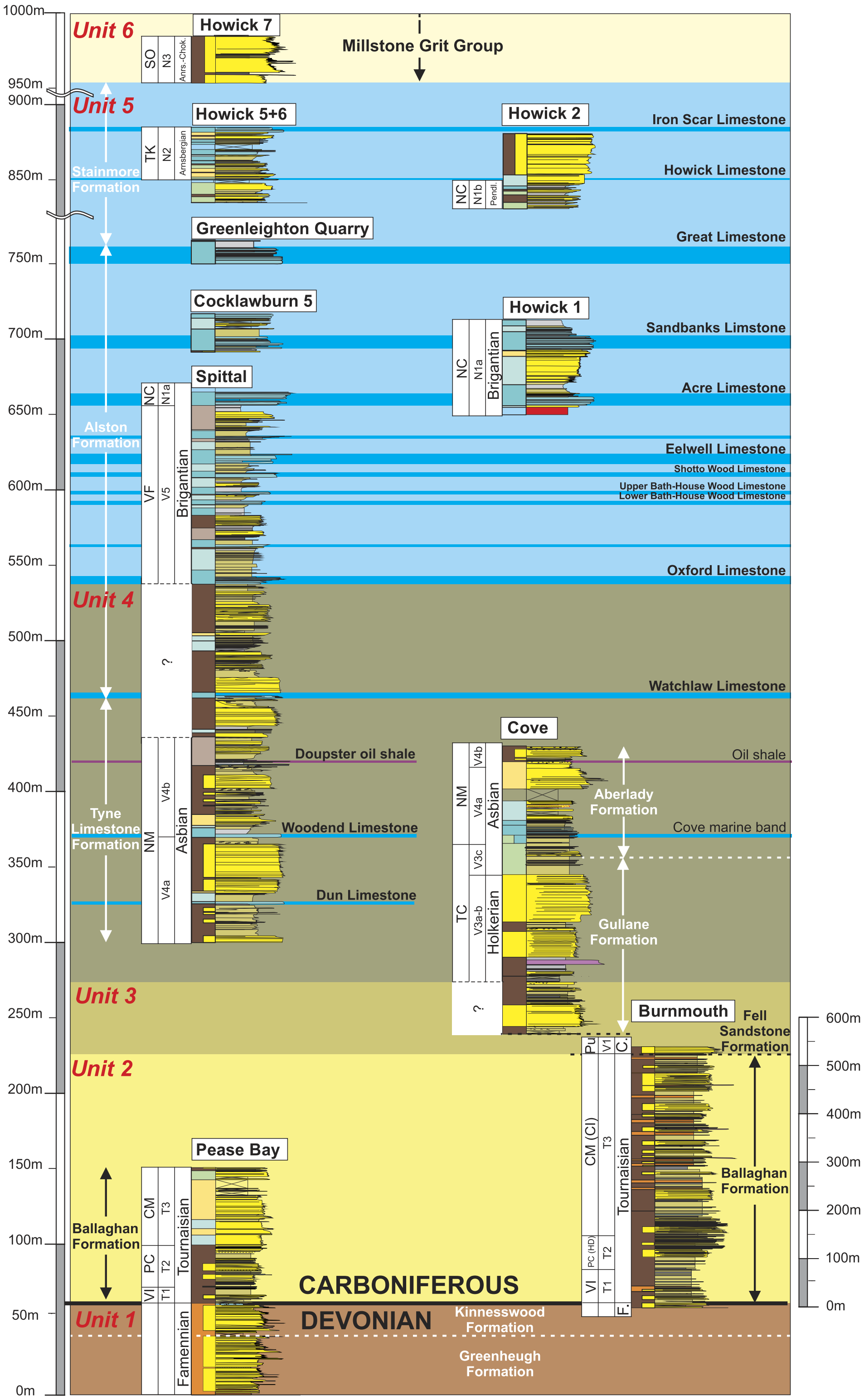

Fig. 4. Measured stratigraphic sections at each outcrop locality are combined into a diagram that highlights stratal relationships within a single correlation panel. Carbonate beds (or bedsets) represent the fundamental tie points for correlation between different sections, and many of them are known to have large areal distribution within the basin. Those intervals that have palynological age controls are marked by three interpretative columns on the left-hand side of the figure (1, Clayton *et al.* 1977 zones; 2, McLean *et al.* 2005 zones; 3, interpreted (Sub) Stage). The coloured areas reflect the seven chronostratigraphic units that are used throughout this contribution. The sections at Cocklawburn, Greenleighton Quarry and Burnmouth were not palynologically analysed in this project but contain either information from the literature (Burnmmouth: Marshall *et al.* 2019; Reeves 2019) or well-known marker beds are sampled. Note the differential vertical scale for Burnmouth.

national borders. This overview is entirely based on the insights from wells and outcrops, with some minor seismic data constraints obtained from the sections presented in Bouroullec *et al.* (2025*b*). This pertains in particular to the presence of the Devonian Kyle Group, which is hardly penetrated by wells, but in some areas is clearly discernible on seismic lines.

In order to better facilitate integration, we have synchronized stratigraphic nomenclature across the study area, in which the offshore UK nomenclature (as summarized by Kearsey *et al.* 2015, 2019 and Whitbread and Kearsey 2016) plays a leading role. In this framework the Cleveland group is introduced for an apparently homogenous succession of shale of Visean–Namurian age. However, the Cleveland group was originally defined by Johnson *et al.* (2011) in the onshore Seal Sands No. 1 Borehole (see discussion on Area 12 below), located south of the Alston Block in the Stainmore Trough (Fig. 6). In this sense, it is used to describe a Holkerian–Asbian succession that is, in places, coal rich and in part analogous to the Yoredale Formation. Therefore, essentially two different concepts of the 'Cleveland group' exist to date. We therefore adhere to the informal status of the Cleveland group to refer to shale-dominated strata and only refer to the formal Cleveland Group *sensu* Johnson *et al.* (2011) whilst describing the Seal Sands No. 1 Borehole stratigraphy.

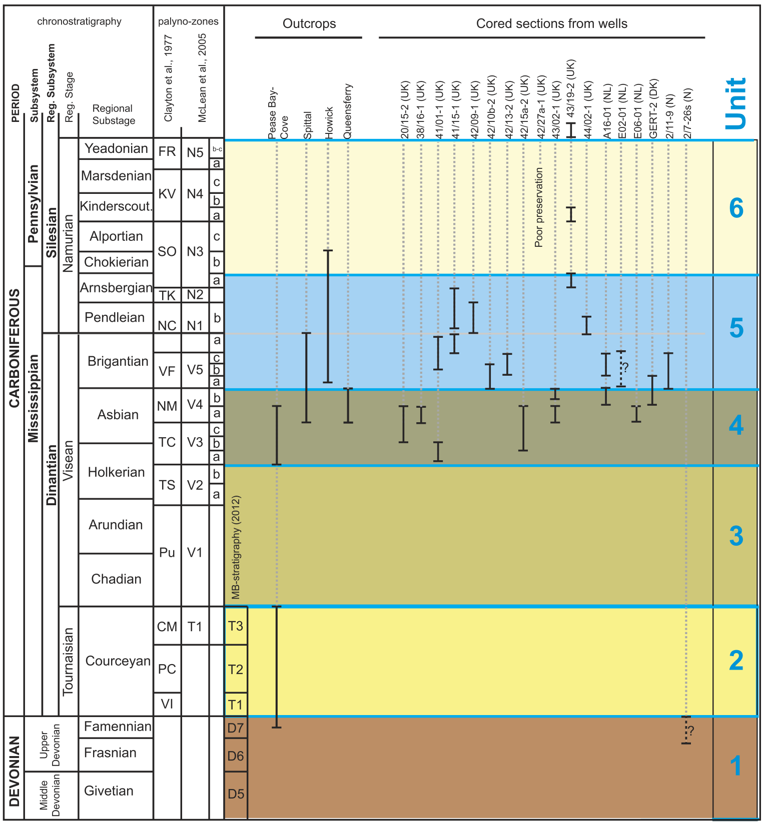

Fig. 5. Overview of the chronostratigraphic coverage of respective offshore core sections. For individual age breakdowns the reader is referred to the Supplementary material. The horizontal shading refers to the chronostratigraphic units as outlined in Figure 7.

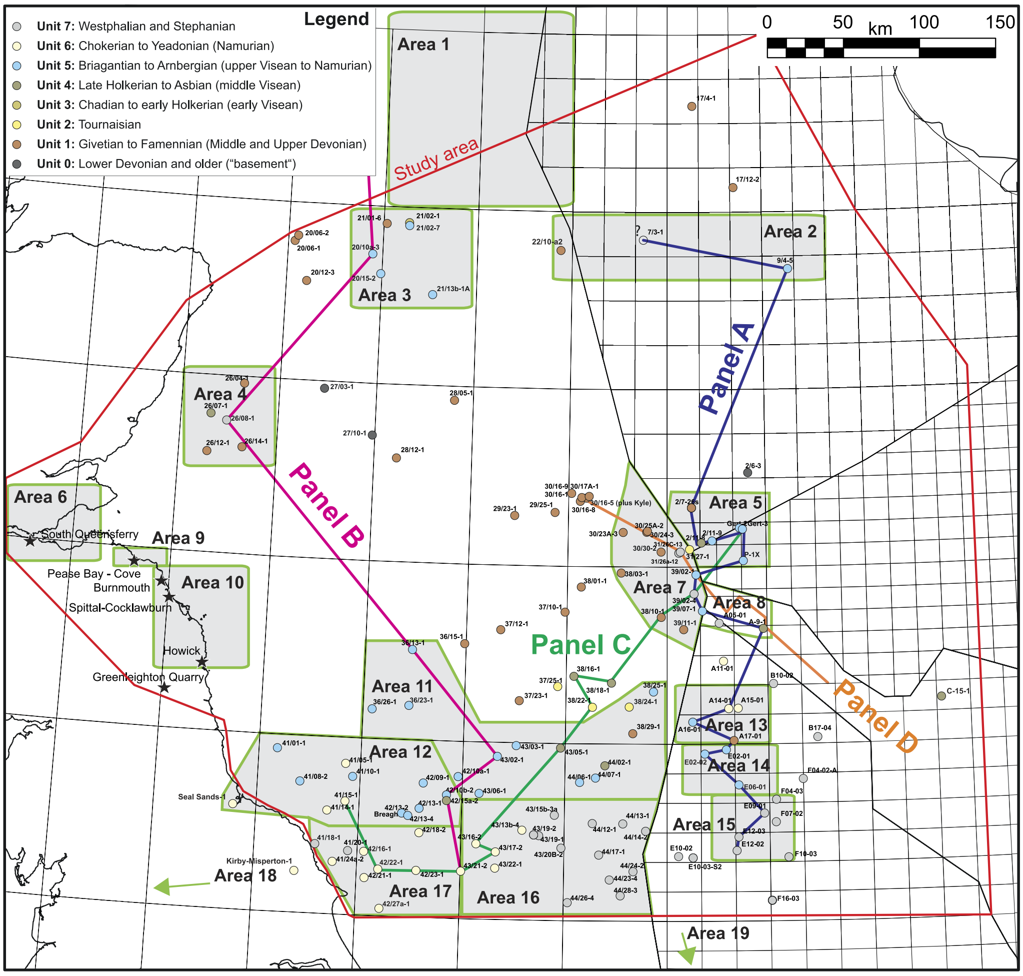

Fig. 6. Map showing the distribution of the areas used to describe the stratigraphic and facies trends throughout the study area. The coloured dots reflect the respective age of the stratigraphy encountered below the BPU, categorized by chronostratigraphic units 1–7. Panels A–D refer to the well sections that are displayed in the supplementary appendices A–D of Bouroullec *et al.* (2025*b*).

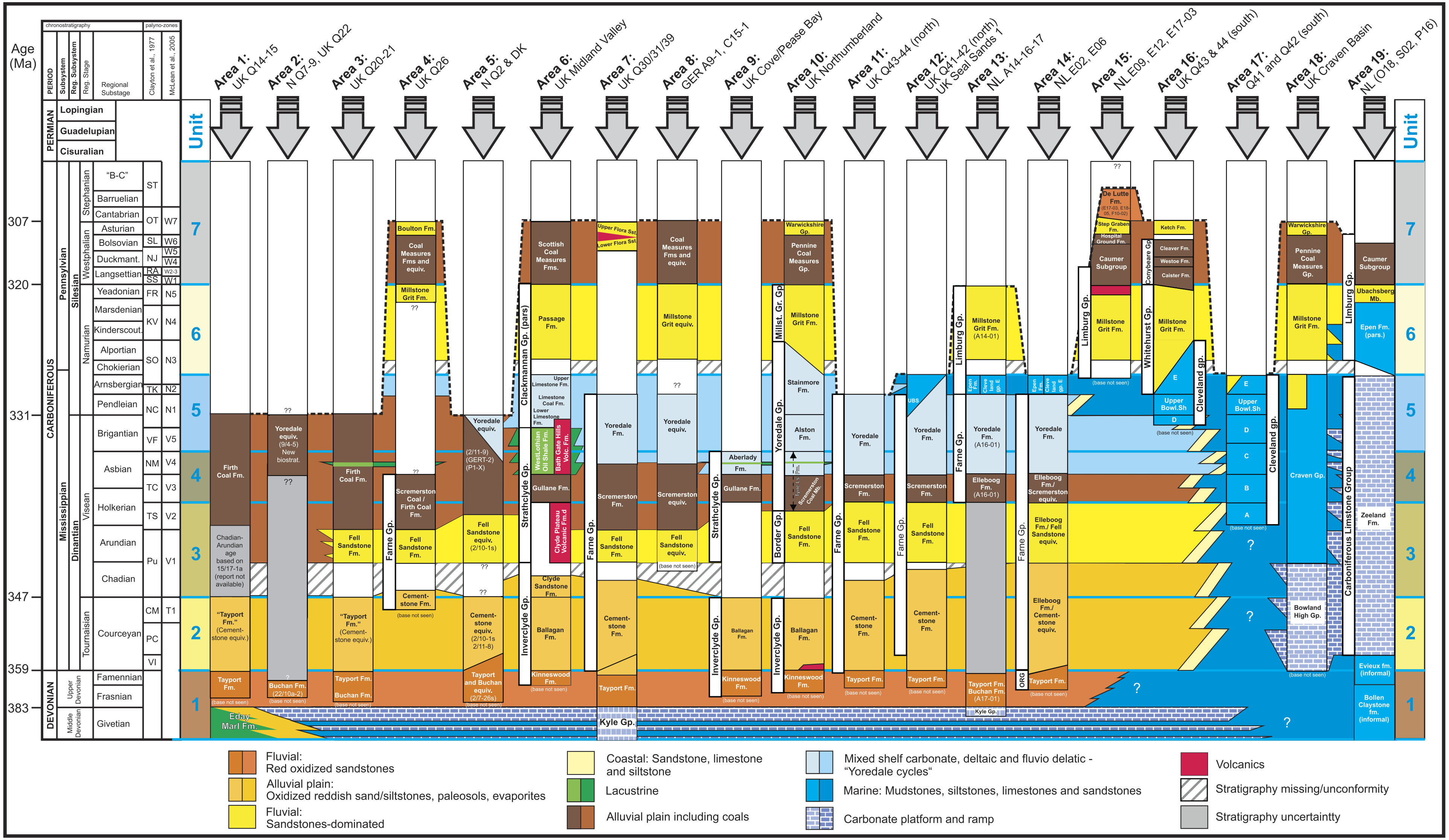

Fig. 7. Stratigraphic facies charts for the different areas of the study area (Fig. 6). The colours indicate the dominant facies type that was deposited during a certain stratigraphic interval (coloured shading). The chronostratigraphic units 1–7 are indicated. UBS, Upper Bowland Shales; GSL, Great Scar Limestone Group.

For the UK outcrop belts, the original lithostratigraphic nomenclature is maintained for reference (Dean *et al.* 2011). Facies definitions largely follow the interpreted lithostratigraphic units and are chosen to be traceable on wireline-log patterns. Where considerable uncertainty regarding the presence of facies of a certain age was encountered, this has been marked by grey background shading in Figure 7. Evident unconformities are marked by black and white striped rectangles. The subsections below follow an overview of the considerations for each of the regional charts. Individual well stratigraphic interpretations are found in Supplementary Appendices D and F. Some of the wells listed below are also part of the stratigraphic correlation panels (shown in Fig. 6), presented in the supplementary appendices A–D of Bouroullec *et al.* (2025*b*).

Area 1: UK Quadrants 14 and 15

Eleven wells penetrating the Lower Carboniferous in UK Quadrants 14 and 15 were evaluated. These wells typically comprise a comparable sequence of the Firth Coal Formation below the Zechstein Group. In wells 14/19-1, 15/03-1 and 15/13-2 older strata are locally referred to as the Tayport Formation. In contrast to the Northumberland area, the Tayport Formation in this area is also used to refer to Tournaisian deposits, implying that continental fluvial deposition continues somewhat longer than in the south. Biostratigraphic evidence for a Tournaisian age for these rocks is available from well 14/19-12 (Rich 1985).

The Firth Coal Formation is identified based on the presence of coal intervals within a mudstone-dominated sequence, with alternations of sandstone, siltstone and, sporadically, some thin limestones. In particular, the coal horizons vary in thickness from a few decimetres to 3 m (Leeder *et al.* 1990). These authors suggest that sediments from the Firth Coal Formation were deposited in a range of environments including fluvio-deltaic, lacustrine, wetland and marine-influenced bay associated with a major deltaic system. The age range of the Firth Coal Formation in UK Quadrants 14 and 15 spans the Visean–middle Namurian. The oldest palynological date for the unit is earliest Visean (Chadian, Pu zone) in well 15/17-1A (Whitbread and Kearsey 2016). However, the underlying report for this claim is not available in the public domain. A more unequivocal age for the base of the Firth Coal Formation in the area is Holkerian (Leeder *et al.* 1990).

Area 2: Norway Quadrants 7–9, UK Quadrant 22

Well penetrations in the pre-Permian are very sparse in this part of the study area. Only wells 9/4-5 and 7/3-1, based on legacy lithostratigraphic interpretations, penetrate pre-Permian strata. The samples from well 9/4-5 provide the only independent evidence of the presence of Yoredale Formation-equivalent strata in this part of the basin (Asbian–Brigantian between 5838 and 5874 m measured depth (MD); see Supplementary Appendix D). Given the far northern locality, a significant marine influence is not expected in the region and, consequently, we tentatively interpreted the dominance of fluvial–deltaic depositional systems in the region.

Well 7/3-1 recovered 5 m of a ‘tight’, pale reddish purply dolomitic limestone below a 286 m-thick Rotliegend-equivalent succession (base Rotliegend at 4692 m MD). As biostratigraphic control is lacking for this interval, it is impossible to evaluate whether these rocks are analogous to a Devonian equivalent (e.g. the Kyle Group), or younger Carboniferous (upper Carboniferous red-bed strata: e.g. see Besly 2005) or Permian equivalents. Well 22/10-a2 on the UK-side of the area penetrates about 500 m of Devonian homogeneous red sandstones assigned to the Old Red Sandstone Formation (Buchan Formation according to Marshall and Hewett 2003) below Rotliegend-equivalent Permian strata.

Area 3: UK Quadrants 20 and 21

Seven wells penetrating the Lower Carboniferous in UK Quadrants 20 and 21 were evaluated. Wells 20/10a-3 and 20/15-2 terminate in the Firth Coal Formation. Wells in the northern half of Quadrant 21 (amongst others in the Buchan Field) penetrate the sequence below the Firth Coal Formation. According to Whitbread and Kearsey (2016), a sequence of the Buchan Formation and the Tayport Formation is present here. The distinction between the two is made on the presence of cyclic sandstone, siltstone and mudstone in the latter. This stands in contrast to Edwards (1991), who assigned the entire Buchan Field succession to the Buchan Formation. According to Whitbread and Kearsey (2016), these rocks reflect deposition in fluvial channel systems, associated overbank deposits and small lakes, much akin to the Cementstone Formation further southwards. Firm biostratigraphic data for the age of the Tayport Formation in the area are not available. Wells 21/01-6, 21/02-1 and 21/02-7 also penetrate the underlying sandstones assigned to the Buchan Formation.

The Fell Sandstone is clearly developed in well 20/15-01. However, as illustrated by Whitbread and Kearsey (2016), the distinction with the overlying Firth Coal Formation is not always clear, especially in cases where the latter occurs as a sandstone-dominated succession (e.g. well 21/12-2B).

The oldest age reported for the Firth Coal Formation in Quadrants 20 and 21 is Holkerian. The youngest reported age is Namurian (Kinderscoutian, KV zone) in well 20/15- 2 (Harris *et al.* 1998). Here, we change this interpretation to Brigantian, or older, by re-evaluation of the ranges of miospore taxa provided by these authors. In addition, the analysis of the core material of this well in the current study provides an Asbian age for the core, which lies in the upper part of the Firth Coal Formation

Bruce and Stemmerik (2003) reported organic-rich lacustrine oil shales in well 20/10a-3 (3915 m). This unit is 6 m thick and is identified by its high resistivity values. AOM-dominated organofacies assemblages in the studied core from well 20/15-2 also point towards the presence of lagoonal or lacustrine, potentially oil-prolific horizons. In both wells, these intervals are dated as Asbian (Unit 4: see Supplementary Appendix D).

Area 4: UK Quadrant 26 (Forth Approaches Basin)

Three wells penetrating the Lower Carboniferous succession in this area were evaluated. Four other wells present the Devonian Buchan Formation below the BPU. Wells 26/07-1 and 26/08-1 have a relevant palynostratigraphic control. Both of these wells display a typical early–middle Visean sequence comprising the Cementstone Formation at the base, a clear sandstone interval ascribed to the Fell Sandstone Formation and coal-bearing strata that can either be assigned to the Scremerston Formation or the Firth Coal Formation. In well 26/07-1, the Scremerston Formation is unconformably overlain by Rotliegend Group sediments. Well 26/08-1 is overlain by a sandstone that underlies Upper Carboniferous coal-bearing strata, grading into the sandy Boulton Formation. This sandstone interval is tentatively assigned to the (Namurian) Millstone Grit Formation-equivalent strata. There are no biostratigraphic data to support this interpretation. Nonetheless, this 126 m-thick sandstone interval may also correlate to the Passage Formation of the Midland Valley area.

Area 5: Norway Block 2 and Denmark Block 5603

In this structurally complex area (see Bouroullec *et al.* 2025*b*), it is important to rely on a mosaic of Norwegian and Danish wells to describe the stratigraphic development. In Norway, well 2/7-26s was selected from the Embla Field to evaluate a mudstone interval above the red-coloured fluvial and conglomeratic strata. These samples turned out barren of palynomorphs, except for some contaminated Carboniferous spores. Consequently, it is most likely that this interval is also composed of Devonian strata equivalent to the Tayport and Buchan formations. Well 2/10-1s recovered 150 m of Carboniferous strata below the BPU. Miospores indicate that the interval between 4560 and 4603 m is of Arundian or older age (Haskins *et al.* 1976). This implies the presence of strata equivalent to the Cementstone Formation. Based on the log character, it is difficult to characterize the depositional facies in this area. Cuttings descriptions suggest the presence of sandstones and green-reddish shales, reminiscent of the Cementstone Formation. Above this Cementstone Formation-equivalent unit, a sandy interval dated as Arundian–early Holkerian was recovered and is analogous to the Fell Sandstone Formation. The interval above this sandy unit is interpreted as equivalent to the Scremerston Formation. Well 2/11-8 shows the presence of Holkerian–Asbian coal-bearing strata (Hydro 1991), which we ascribe to the Scremerston Formation, overlain by Upper Jurassic–Lower Cretaceous rocks of the Tyne Group. Interestingly, two large, probably intrusive, volcanic units occur in this interval.

Cored intervals from Norwegian well 2/11-9 and Danish well Gert-2 were studied palynologically (see Supplementary Appendix D). These cores are Brigantian and Asbian–Brigantian in age, respectively. Well 2/11-9 extends *c.* 150 m below this cored interval. Based on the well-log character, the interval becomes more coal-rich downsection. Hence, it is likely that Scremerston Formation-equivalent strata were reached. A similar pattern is observed in the Gert-2 well, which extends for another 110 m below the Asbian-age bottom of the core. Conspicuous limestones were not recorded in neither the cores nor the well-log sections of these wells. Marine mudstones were, however, observed in cores from both wells, indicating that marine conditions had developed. This suggests that the typical ‘Yoredale cyclicity’ lacks limestone development in the upper Asbian and Brigantian in this part of the study area. The Visean in the Gert-2 well is overlain by Upper Jurassic (Kimmeridgian) strata. For Danish well P1-X, the stratigraphic information provided by the well-data summary sheets from the GEUS website suggests that the Rotliegend strata overlie undifferentiated Lower Carboniferous strata.

Area 6: Midland Valley of Scotland

The stratigraphic chart for the Midland Valley of Scotland area follows Dean *et al.* (2011) and Kearsey *et al.* (2015). Of relevance are the extensive lacustrine oil shales that were deposited during Asbian and Brigantian times. A representation of part of the West Lothian Oil-Shale Formation was sampled for this study in South Queensferry (see Fig. 2 for the location; see also Supplementary Appendix C5 for the details).

Area 7: UK Quadrants 30, 31, 38 and 39

On the Dogger High and Mid North Sea Platform area, UK wells 30/25a-2, 30/24-3 and 38/03-1 penetrate the middle Devonian Kyle Limestone Group. Well 38/03-1 displays a characteristic section from the Kyle Limestone Group, an upward-coarsening Buchan Formation sequence, overlain by typical cyclical Tayport Formation sandstones and claystones below the BPU. The Cementstone and Fell Sandstone formations are not recorded in wells from the area. Wells in UK Quadrant 39 do not extend to these depths, whereas the wells on the structural high to the west (Auk Ridge) have Devonian subcropping the BPU. However, based on seismic stratigraphy, the Lower Carboniferous interval appears to be present (Bouroullec *et al.* 2025*b*).

Well 39/07-1 terminates in the Scremerston Formation, which comprises relatively thick coals (clearly discernible on the wireline-log scale). The Yoredale Formation, with its characteristic limestone units, is encountered further upsection. A similar, yet apparently mud-prone, Yoredale Formation is also encountered in well 39/02-1. In both wells, the Yoredale Formation is unconformably overlain by siltstones and sandstones assigned to the Grensen Formation. Whether this formation is Early Permian or latest Carboniferous (Stephanian) in age has been debated, but Bouroullec *et al.* (2025*a*), building on the work of Martin *et al.* (2002), correlated these strata to the early Permian pre-Saalian Unconformity, like the Lower Rotliegend Group of the northern part of the Dutch offshore. The late Westphalian Flora Sandstone Formation and its associated extrusive volcanics that separate the lower and upper part of the formation are encountered in wells 39/02-4, 31/26a-12 and 31/26c-13 (Martin *et al.* 2002).

Area 8: Germany Blocks A and C

In the German sector of the North Sea Basin, well A-9-1 provides an insight into the stratigraphy of the Lower Carboniferous. Only the gamma-ray log and sonic velocity-log data were available, and no biostratigraphic data or samples were available. Based on the characteristic log pattern, we follow the interpretation proposed by Doornenbal and Stevenson (2010), which was subsequently also adopted by Ter Borgh *et al.* (2019*a*). The roughly 900 m-thick Carboniferous succession is characterized by 75 m of sandstones above total depth (TD) at 4384 m. This succession is interpreted as an equivalent of the Fell Sandstone Formation. Above, 237 m of very cyclical sand, silt-mudstone and relatively thick coals are interpreted as an equivalent of the Scremerston Formation. Upsection, an increasing sand and limestone content is interpreted as equivalent of the Yoredale Formation (362 m thick). The latter grades into a thin relatively ‘shaly’ Millstone Grit Formation equivalent that might alternatively be assigned to the Cleveland group. Above that 50 m of coals, silt, mudstones and sandstones reappear, as reflected in an electrofacies log that bears a strong resemblance to the underlying Scremerston Formation equivalent. This is interpreted as Upper Carboniferous coal measures. Above the BPU, the Zechstein Group is present. Well C-15-1 is included in a well-section panel in Doornenbal and Stevenson (2010, fig. 6.6). The *c.* 500 m section below the BPU is ascribed to the Tayport, Cementstone and Fell Sandstone formations, and a thin sliver of Yoredale Formation/Scremerston Formation-equivalent strata. No further data were considered at the time of writing this paper.

Area 9: Onshore SE Scotland: Cove and Pease Bay outcrop sections

The stratigraphic relationships drawn for this area are based on our study of the outcrop sections at Pease Bay and Cove (Fig. 2; see also Supplementary Appendix C). The lithostratigraphy of the units is after Dean *et al.* (2011). The section spans the Devonian– Carboniferous boundary, which is expressed by the transition from red-bed fluvial sandstones to the characteristic paralic marine to coastal-plain facies of the Ballagan Formation with characteristic Cementstone beds (i.e. Cementstone Formation equivalent: see Marshall *et al.* 2019). The Fell Sandstone Formation is not exposed at Pease Bay and Cove, which may be due to the unconformity and/or fault (the Cove Fault) that truncates the Ballagan Formation at its top. The Gullane Formation is of Holkerian age and consists of alterations of floodplain siltstones, sandstones and coals (Fig. 4). This is comparable to what is reported for the Scremerston Formation elsewhere. The top part of the Gullane Formation is locally expressed by a large channel complex locally termed the Heathery

Heugh Sandstone Member. The overlying Aberlady Formation consists of a basal part of paralic marine and floodplain siltstone beds and one conspicuous limestone bed (e.g. the Cove Lower Marine Bed). This interval is dated as mid-Asbian (Fig. 4). Close to the top of the Cove section we recorded three conspicuous lagoonal to lacustrine oil-shale beds and a coal layer. These are locally contained in the Kip Carle Member; this interval is dated as late Asbian.

Area 10: Onshore SE Scotland and NE England: Burnmouth, Spittal and Howick outcrop sections

The stratigraphic chart for Area 10 is based on our observations and analyses on the sections at Burnmouth, Spittal and Howick (Fig. 4). The lithostratigraphic nomenclature is outlined in Waters *et al.* (2011). Note that the naming of the onshore Scremerston Coal Member as part of the Tyne Limestone Formation as opposed to the offshore Scremerston Formation may lead to confusion, which cannot be resolved in this contribution. The Fell Sandstone Formation is well exposed at Burnmouth (Fig. 2; see also Supplementary Appendix C, Fig. C2) and at several other inland sections farther south in Northumberland (e.g. at Bowden Doors). The age range is Chadian–late Holkerian. Only a very small part of the overlying Scremerston Coal Member of the Tyne Limestone Formation was studied by us (i.e. the basal 27 m of the Spittal section: Fig. 2; see also Supplementary Appendix C, Fig. C3) below the first limestone bed (Dun Limestone). Elsewhere in the region, the Scremerston Coal Member is described to range down into the Holkerian (see Jones 2007; Kearsey *et al.* 2019 and references therein).

Upsection, the cyclical nature of limestone units, defining the so-called Yoredale cycles, is well expressed. The ‘Doupster Oil Shale’ is a thin, potentially oil-prone source rock in the upper Asbian of the Tyne Limestone Formation. As such, it is coeval to the oil shale units recorded at Cove, Queensferry, and in wells 20/15-2 and 21/10b-3. Similar lacustrine–lagoonal intercalations are not reported in the underlying Scremerston Coal Member or in onshore coal boreholes (Jones 2007). The remainder of the Asbian Yoredale Formation-equivalent Tyne Limestone Formation at Spittal is characterized by relatively thin limestone and coal beds compared to the overlying Brigantian Yoredale Formation-equivalent section of the Alston Formation (above the Oxford Limestone). The limestones become more pronounced and there is also a larger proportional thickness of marine mudstone facies. The base of the section in Howick (Fig. 2; see also Supplementary Appendix C, Fig. C4) rests immediately upon the intrusive Whin Sill, and is more or less time equivalent with the top of the Spittal section. Namurian (Pendleian–Chokierian: see Turner and Spinner 1992) rocks characterized by Yoredale cyclicity are assigned to the Stainmore Formation. The transition into the overlying Millstone Grit Formation, observed at Howick, is known to be diachronous (see also Kearsey *et al.* 2019).

Area 11: UK Quadrants 38, 39, 43 and 44

In the northern part of Quadrants 43 and 44, only well 44/02-1 penetrates strata as old as the Upper Devonian Tayport Formation. This well and well 43/02-1 penetrate the overlying Tournaisian Cementstone Formation. In the latter well, only a very thin section below the Fell Sandstone Formation was drilled. Here, the transition is of Chadian–Arundian age (Paleoservices 1989). We follow the age for the base of the Fell Sandstone as suggested by Kearsey *et al.* (2016). The Scremerston Formation is recorded in wells 43/02-1, 44/02-1 and 44/06-1. We studied cored sections in the former two wells. In the core from 43/02-1, the lower Asbian Scremerston Formation (NM-Zone, Zone V4b) is characterized by relatively thick coals, extensive deltaic sandstones and, interestingly, also by two prominent limestone beds. This illustrates that the Scremerston Formation to the south becomes progressively more marine, with an ‘earlier’ onset of Yoredale cycles. The Yoredale Formation is recorded in most of the wells in the area, with numerous wells suggesting, based on biostratigraphic data, an age range between Asbian and Pendleian. In this area, the top of the Yoredale Formation is unconformable, with the remainder of the Carboniferous being absent.

Area 12: Northern part of UK Quadrants 41 and 42, and the onshore Seal Sands No. 1 Borehole

For the Tournaisian and lower Visean, the wells in this area display a similar stratigraphic development as in Area 11. Well 41/01-1 has a thin Cementstone Formation sequence before it reaches TD. McLean (2012) demonstrates that this upper part of the Cementstone Formation is of Arundian age. Well 42/10b-2 also has a clear Cementstone Formation developed. Unfortunately, no biostratigraphic data exist for this interval. The overlying Fell Sandstone Formation is locally 129 m thick in well 41/01-1 and is of Holkerian age (McLean 2012). Perhaps remarkably, the Fell Sandstone Formation here, according to the sedimentology observed (see Supplementary Appendix A), also contains marine facies. Shallow-marine to pro-deltaic Holkerian–early Asbian (our chronostratigraphic units 3 and 4) depositional environments are also encountered in the onshore Seal Sands No. 1 Borehole, located onshore UK just south of the Alston Block. Here, a thick (>2000 m) sequence of coal-bearing, finely bedded mudstone and sandstone, with an occasional marine influence indicated by very thin limestone streaks, is encountered below the appearance of prominent limestone–coal cyclicity by late Asbian times. These Holkerian–early Asbian coal-bearing, mudstones are referred to as the Cleveland Group by Johnson *et al.* (2011). They divide the Cleveland Group into the Seal Sands, Teesmouth and Greatham formations. Noteworthy here is that the youngest of these formations (e.g. the Greatham Formation) is already characterized by well-developed limestone beds, which stand in contrast to the base of the Yoredale Group, and is drawn above the Great Scar Limestone Group. A marine influence is also evident in the Scremerston Formation of well 41/01-1, much in line with what is seen in Area 11. In wells 41/01-1 and 41/10-1, this interval has a latest Holkerian (TC-Zone, Zone V3c) to mid-Asbian age (NM-Zone, Zone V4b: McLean 2012). In well 41/01-1, the upper part of the Scremerston Formation becomes more carbonate-rich (Kearsey *et al.* 2019).

At the Seal Sands No. 1 Borehole, the Yoredale Group strata, as interpreted by Johnson *et al.* (2011) (Brigantian–Arnsbergian, our chronostratigraphic Unit 5), lie above the Great Scar Limestone Group, which here consists of two prominent limestone beds: viz. the Melmerby Scar Limestone and the Robinson Limestone. These are thought to 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 late Asbian. Subsequently, the Yoredale Group, as interpreted by Johnson *et al.* (2011), is here Brigantian–Arnsbergian in age and equates to a thickness of 1100 m. The Pendleian–Arnsbergian top of the Yoredale Group is truncated by the BPU at the Seal Sands No. 1 Borehole.

The Yoredale Formation is recovered in all selected offshore wells in the area. Its age range is Asbian–Pendleian. Towards the top, well-log profiles display interfingering with the basinal shales of the Upper Bowland Shale Formation of the Cleveland group (e.g. see well 41/14-1). The Yoredale Formation includes the reservoir facies of the Breagh Field (Booth *et al.* 2020) in Block 42/13. The Namurian in much of this area is characterized by interbedded sandstones in an overall mudstone-dominated succession (e.g. in the Kirby Misperton 1, 41/24A-2 and, albeit fragmentary, 41/

14-1 wells). These are considered as relatively deep-water sediment gravity flows. Whether these can be considered reminiscent of the Millstone Grit Formation can be questioned. For the sake of consistency they are indicated as such in Figure 7.

Area 13: Southern part of Dutch A Block

Wells A14-01, A15-01, A16-01 and A17-01 collectively provide valuable insights into the development of the Lower Carboniferous stratigraphy in the Dutch northern offshore. Note that well A17-01, on the Elbow Spit High in the south of the area, has recovered a *c.* 1100 m-thick Devonian succession of fluvial red beds assigned to the Buchan and Tayport formations. This Devonian succession is intercalated by two rhyolitic igneous intervals and overlies plutonic basement, and is unconformably truncated by Upper Cretaceous Chalk Group sediments. The dating of these igneous rocks is controversial (Early Carboniferous, 341 Ma; Van Bergen *et al.* 2025). These authors correlate the A17-01 igneous rocks with rhyolites with highly altered quartz porphyries in the Embla oil field (Norway, Block 2/7), which have been dated at 374 ± 3 Ma (zircon U–Pb age). These represent a Late Devonian (Early Famennian) volcanic episode (see also Lundmark *et al.* 2018).

Well A16-01 terminates in the Yoredale Formation. Core samples near TD were analysed in this study and yielded a late Asbian (NM-Zone, Zone V4b) age (see Supplementary Appendix D). A second core interval near the top of the Yoredale Formation yielded a Brigantian (VF-Zone, Zone V5a) age (see the Supplementary material). In terms of wireline-log character, the Yoredale Formation is expressed in a very characteristic manner with alternations of silt-mudstones, limestones, sandstones and coals. Coal strata appear more expanded in the basal (Asbian) part of the succession. The Yoredale Formation is unconformably overlain by Rotliegend Group-equivalent sediments of the Lower Slochteren Member.

Well A15-01 has recovered a presumed Namurian (Millstone Grit) succession that is intercalated with two intrusive igneous layers. No biostratigraphic data are available and, hence, the interpretation is primarily based on wireline-log character. Well A14-01 penetrates an extensive Lower Carboniferous succession. The well terminates in the Elleboog Formation (Scremerston Formation equivalent) and is overlain by the Yoredale Formation. The latter becomes progressively more dominated by silt-mudstone lithologies and grades into the Namurian Epen Formation (Cleveland group E equivalent). Based on the wireline-log character, we see no reason to infer the presence of a Pendleian hot shale (Upper Bowland Shale or, in Dutch nomenclature, Geverik Member). Igneous rocks intrude the Epen Formation/Cleveland group E. Subsequently, sand, silt-mudstone and coal strata overlie the silt-mudstones, which arguably correspond to the Millstone Grit Formation.

Area 14: Dutch Blocks E02 and E06

Wells E02-01, E02-02 and E06-01 form the basis for the stratigraphic chart for Area 14. Well E02-01 penetrated *c.* 600 m of Devonian and Lower Carboniferous strata below the Chalk Group. The well terminates in cyclic silt-mudstone and sandstone intercalations that we have assigned to the Tayport Formation. TNO-GSN has legacy palynological data from NAM (Nederlandse Aardolie Maatschappij) available. We also consulted a very brief biostratigraphic summary report (NAM 1972). The Tayport Formation sediments are barren of palynomorphs. Upwards, clear sonically ‘fast’ limestone beds occur, characteristic of the Cementstone Formation that was previously assigned to the Dutch Elleboog Formation. The palynology becomes productive in this interval and comprises a typical Tournaisian association (containing *Auroraspora macra* and *Verrucosisporites nitidus*) below 2370 m MD and a typical early Visean (Chadian or younger) association (now containing *Lycospora pusilla*) for the upper part of the Cementstone Formation. A record of *Spelaeotriletes pretiosus* in the sandy interval between 2250 and 2300 m MD supports the presence of a Fell Sandstone Formation equivalent of Holkerian age. Above this Fell Sandstone equivalent, 120 m of lower Asbian strata are recorded. These are interpreted as a Scremerston Formation equivalent. Remarkably, based on wireline-log characteristics, the typical coal layers seem to be absent. In the overlying 80 m of upper Asbian–Brigantian strata, both coals and (thin) limestones become discernible in the wireline-log character. Above the Yoredale Formation the succession becomes more dominated by silt-mudstones, which we interpret as the Epen Formation, an analogue of the Cleveland group E. Namurian hot shales are not clearly recorded. Biostratigraphic data are absent for this part of the section. The Chalk Group subsequently overlies this Carboniferous succession.

Well E02-02 (see supplementary appendix A in Bouroullec *et al.* 2025*b*) terminates in upper Holkerian strata (based on NAM legacy data), the basal part of which may correspond to the Fell Sandstone Formation. The overlying 50 m are interpreted as a Scremerston Formation equivalent. In this interval, two prominent coal layers are observed on wireline logs. Subsequently, a 166 m-thick section above 2516 m MD is Asbian–Brigantian in age and is interpreted as the Yoredale Formation. Remarkably, well E02-01 contains very thick (up to 10 m) limestone beds, whereas coals are not discernible. The Yoredale Formation is unconformably overlain by a very thin Lower Permian Silverpit Formation below the Zechstein Group.

A similar development of the Yoredale Formation is observed in well E06-01. However, this well also contains a characteristic sequence of the older part of the Upper Devonian and Lower Carboniferous. The only biostratigraphic report on the well claims that the entire sequence is barren of palynomorphs (Van de Laar 1992); however, in the context of the current study, the core yielded discernible palynomorphs (see Supplementary Appendix D). The well terminates in a typical Tayport Formation-equivalent facies. This 444 m-thick interval represents alternations of silt-mudstones and thin sandstone beds. The top is clearly defined by the appearance of ‘fast’ lime-/cementstone beds, characteristic of the Cementstone Formation. The Cementstone Formation equivalent is *c.* 200 m thick. Neither the Fell Sandstone Formation equivalent nor the Scremerston Formation equivalent are developed in a typical facies, showing neither clear sandstone nor extensive coal layers. It is therefore indicated in local Dutch nomenclature as the Elleboog Formation, of which E06-01 is the type section. The Elleboog Formation is intruded by a 25 m-thick intrusion (see supplementary appendix A in Bouroullec *et al.* 2025*b*). The Yoredale Formation is composed of thick limestones and well-developed coals similar to those found in well E02-02. The base of the Yoredale Formation is mid-Asbian (NM Zone, Zone V4a: see Supplementary Appendix D). The Yoredale Formation is unconformably overlain by the Lower Permian Silverpit Formation.

Area 15: Dutch Blocks E09, E12 and E17

According to the Dutch well-top database, wells E09-01, E12-02 and E12-03 all terminate in the Millstone Grit Formation (see supplementary appendix A in Bouroullec *et al.* 2025*b*). Considering the wireline-log character of well E12-02, a downward transition to the Yoredale Formation is possible, based on the occurrence of limestone beds. Wells E09-01 and E12-03 encountered intrusive volcanics. The Upper Carboniferous (Klaverbank Formation) overlies the Millstone Grit Formation in these wells. There is limited biostratigraphic control for well E12-03 (Van de Laar 1992), suggesting an Arnsbergian–Yeadonian age for the Millstone Grit

Formation. In well E17-03, a Stephanian section is recognized and referred to as the De Lutte Formation below the BPU.

Area 16: Southern part of UK Quadrants 43 and 44

In the southern half of Quadrants 43 and 44 no strata older than Brigantian have been reached. This is a consequence of the deeper burial depth of the Carboniferous in the area. Wells 43/21-2 and 43/17-2 contain Brigantian deep-water shales, assigned to Cleveland group D (Kearsey *et al.* 2015). The overlying shales of Pendleian age are often characterized by elevated gamma ray (GR)-log readings and assigned to the Upper Bowland Shale Formation of the Cleveland group. However, these characteristic wireline-log readings are not always present. In well 43/19-2, the elevated GR reading is not identified in the Pendleian part of the succession; while in well 44/17-1 (4855 m MD), a characteristic GR-signature for the Upper Bowland Shale Formation is recognized. This could be ascribed to the coeval feeding of deeper-water fan systems into this hemipelagic basin. This would lead to regional interfingering between the 'Millstone Grit' and the 'Bowland Shale' facies type. Subsequently, the Millstone Grit facies extended progressively southwards across the area culminating in Kinderscoutian times. By this time, the basinal silt-mudstones of the Cleveland group were no longer being deposited (Collinson 2005). Eventually, several wells encountered the Westphalian coal measures.

Area 17: Southern part of UK Quadrants 41 and 42, and the onshore Seals Sand No. 1 Borehole

In contrast to the neighbouring Area 16 in the east, Area 17 is characterized by an extensive Lower Carboniferous shale–mudstone-dominated sequence assigned to the Cleveland group *sensu* Kearsey *et al.* (2015). Sediments older than Holkerian have not been penetrated. Well 42/16-1 recovered a 1200 m-thick succession assigned to the Cleveland group (units A–E). According to Kearsey *et al.* (2019), the age of the basal Cleveland group (A) is Holkerian. Well-log profiles show that the Cleveland group in the area, as a whole, consists of homogenous units of shale exceeding 100 m in thickness, interbedded with cycles of limestone, sandstone, mudstone and sporadic coals. A similar, *c.* 1400 m-thick, succession is recorded in the onshore Kirby Misperton 1 well.

In the upper part of the Cleveland group, there is a high GR unit of black shale, which Cameron (1993) termed the Bowland Shale Formation. In analogy to Kearsey *et al.* (2019), we refer to the high GR unit as the Upper Bowland Shales to avoid direct comparison with the eponymous formation, which has a wider definition and age range across northern England (Aitkenhead *et al.* 2002).

Kearsey *et al.* (2019) attempted a correlation of shale packages beneath the Upper Bowland Shales. For example, unit D shows consistent characteristics across many of the wells, although units A–C below this cannot be easily correlated between wells. Coals are absent from the lower part of the Cleveland group in the Kirby Misperton 1 well, suggesting that this part represents a mudstone-dominated pro-delta succession. By contrast, the apparent intercalation of Yoredale Formation 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 the Seal Sands No. 1 Borehole (in Area 12), more closely resemble the Yoredale Formation. Biostratigraphic data from the Kirby Misperton 1 well indicate that the Cleveland group units below the Upper Bowland Shales lie within the Arundian–Brigantian interval (Kearsey *et al.* 2019). The overlying Upper Bowland Shales contain upper Brigantian and Pendleian miospores. The highest unit (E) in the group in Quadrant 41 and the Kirby Misperton 1 well has yielded Pendleian–Arnsbergian ages, whereas in Quadrant 43 this range extends into the Alportian (Kearsey *et al.* 2019).

In this area, the Millstone Grit lithofacies is not developed, probably because of erosion during the formation of the BPU.

Area 18: UK onshore: Craven Basin

The stratigraphic chart for the Craven Basin (modified after Dean *et al.* 2011), shown here to provide context to the far SW of the study area, is simplified to the generic Group level. In essence, the stratigraphy is characterized by Tournaisian platform carbonates of the Bowland High Group. The Craven Group is a lithostratigraphic term referring to the succession of mudstone and limestone strata. Its age range is Chadian–Yeadonian. Other lithologies including sandstones, siltstones and chert occur within the group. By analogy to what is recorded further to the east, the Millstone Grit lithofacies becomes more prominent during the later stages of the Namurian. The Westphalian consists of coal-bearing strata of the Pennine Coal Measures Group (Dean *et al.* 2011).

Area 19: Dutch southern offshore Blocks O18 and P16

The chart for Area 19 provides context for the development of the Lower Carboniferous further south of the study area. Here, hemipelagic deposition of the (informal) Bollen Claystone formation characterizes the middle and lower part of the Upper Devonian. The fine micaceous sandstones and initial Strunian limestones and dolomites of the late Famennian are now termed the Evieux formation in analogy to the Belgian stratigraphy (see Vis *et al.* 2025). These transitional strata were formerly referred to as the informal Bosscheveld formation. Note that the Old Red Group is no longer recognized this far south. During the Tournaisian and Visean, a carbonate ramp fringed the northern part of the London Brabant Massif (Reijmer *et al.* 2017; Vis *et al.* 2025). The Zeeland Formation is used in The Netherlands to describe a range of carbonate-bearing facies (Vis *et al.* 2025). The hemipelagic claystones and siltstones (the so-called Kulm facies) were deposited away from the shallow-water carbonate factories. The top of the Zeeland Formation limestone sequences is typically unconformable and corresponds to the base of the Namurian (Van Adrichem Boogaert and Kouwe 1993; Huis in 't Veld and Den Hartog Jager 2025). Overlying Namurian siltstones and mudstones assigned to the Epen Formation are encountered, which developed as part of the incipient foreland basin of the Variscan orogen (Huis in 't Veld and Den Hartog Jager 2025). The upper (Yeadonian) part of this package becomes more sandy, associated with distal delta-front deposition (Ubachsberg Member). The hot shales of the Geverik Member (Upper Bowland Shale Formation equivalent) are not encountered in the area as they typically occur in structural lows away from the carbonate ramps and build-ups.

The major facies-distribution patterns through time are drawn as a background to Figure 7 in order to provide an overall stratigraphic and palaeoenvironmental template for the remaining parts of this paper. In general, an overall north–south general proximal to distal trend is maintained. A further discussion of these trends is given in the final section of this paper and the four palaeogeographical maps are presented in a companion paper (Bouroullec *et al.* 2025*b*). Two major unconformities are discernible in all regions near the base of the Visean, at the onset of the Fell Sandstone depositional cycle and in the mid-Namurian, and are overlain by the Millstone Grit depositional cycle. For the Base Visean Unconformity (BVU), we hypothesize that is of eustatic origin. First, stable oxygen isotope compilation studies (e.g. Buggisch *et al.* 2008) indicate a step towards heavier values, indicating cooling and/or continental ice-sheet build-up across the Tournaisian–Visean boundary. Next, major regional highs (e.g. Cheviot block and granite) sourced the

Fell Sandstone Formation (Howell *et al.* 2022), which indicates that local highs were either exposed and/or eroded during a significant sea-level fall, or that local uplift occurred along some basement faults. In either case, the sediment volume contained in the Fell Sandstone Formation and equivalent formations is so vast, and the source so far from the study area, that a structural uplift on the scale of the study area would have been very unlikely.

For the mid-Namurian unconformity, coeval uplift of the Norwegian–Greenland Sea region to the north has been postulated as an important sediment source (Morton and Whitham 2002), suggesting that a tectonic component is prominent as a causal factor for this regional unconformity.

Palaeoenvironments and vegetation development through time

The following section first presents a short summary of the larger-scale regional trends discernible from wireline-log correlation and legacy data for selected time units. Note that illustrative regional correlation panels and palaeogeographical maps are presented and discussed in Bouroullec *et al.* (2025*b*, fig. 15). These summaries are then further complemented by discussing organofacies and palynological composition data (Fig. 8; Table 4). These collectively provide insight into changes in the depositional environment through time. This synthesis aids to constrain observations made with regard to source-rock potential in the succeeding section.

Devonian (Unit 1)

The Devonian comprises the oldest strata that are considered in this study, even though they were not sampled in the Middle Devonian (Givetian: Kearsey *et al.* 2015, 2019) Kyle Limestone Group. This unit is of particular importance given its strong expression on seismic data (see Bouroullec *et al.* 2025*b*, figs 10 and 11). However, it is only rarely penetrated by wells and, if so, only on structural highs such as the Dogger High, Auk Ridge and the Elbow Spit High (see also Bouroullec *et al.* 2025*b*). The marine carbonate facies of the Kyle Limestone Group thins to the north and is likely to pass laterally into clastic-dominated strata consistent with shallow-marine conditions over the northeastward extension of the Southern Uplands block (Whitbread and Kearsey 2016). The Kyle Limestone Group is characterized by limestone units separated by shale and sabkha facies. The limestone is dominantly bioclastic, containing tabulate and rugose corals, ostracods, brachiopods, bivalves, gastropods, and crinoids (Marshall and Hewett 2003). The deposition of marine limestones in the study area is related to a prolonged Middle Devonian eustatic maximum, linked to a persistent greenhouse climate that culminated before the Late Givetian Taghanic unconformity (Johnson *et al.* 1985; Brett *et al.* 2011). North of the study area, an extensive development of lacustrine deposits of middle–late Givetian age is found in the northern part of the Orcadian Basin. These strata are assigned to the Eday Group (Whitbread and Kearsey 2016). A major highstand phase in the lake level has been associated with the John O'Groats Fish Bed within lake-marginal fluvial successions that similarly predate the Taghanic phase (Marshall *et al.* 2011). The lacustrine conditions were preceded and succeeded by alluvial deposits of the Lower and Middle Eday Sandstone formations (Marshall and Hewett 2003). An extensive sabkha plain developed, giving rise to the Eday Marl Formation. Marshall and Hewett (2003) proposed that the Eday Marl Formation is a proximal equivalent of the Kyle Group in the current study area. They also highlight evaporites (anhydrite) of Givetian–Frasnian age encountered in wells in Quadrants 8 and 9, and to the south of the Grampian High in UK Quadrant 20, noting that these units may be associated with evaporitic lagoons formed along the former marine margin. The nature and location of the transition between the sabkha and the marginal-marine system are poorly known due to a lack of well penetrations. The association of marine carbonates, marginal evaporites and sabkha is consistent with a seaway located to the south and east (Marshall *et al.* 2011). Subsequently, the sabkha conditions were superseded by a return to alluvial deposition during the Late Devonian, giving rise to the Buchan Formation. The consequent development of more pronounced overbank deposits, including small ephemeral lakes, sets the stage for defining the Tayport Formation (Leeder *et al.* 1990; Cameron 1993). This transition occurs earlier (late Famennian–early Tournaisian) in the 'Paleo-Five Project' area than in the more northerly Forth Approaches and Orcadian areas, where the Tayport Formation is of Visean age (Fig. 7) (see also Cameron 1993).

The oldest chronostratigraphic unit (Unit 1) of this study comprises the Tayport Formation and the onshore Kinneswood Formation (see Bouroullec *et al.* 2025*b*, figs 4 and 5). These red-bed-dominated lithologies were predominantly deposited under alluvial conditions throughout much of the study area. Samples were obtained only from outcrop sections of Burnmouth and Pease Bay for the Tayport Formation, but no palynological analyses were performed (see Supplementary Appendix A). Rock-Eval analyses show that the sediments exposed in the outcrops are consistently organic lean, which is in line with the depositional environment inferred from sedimentological observations.

Tournaisian (Unit 2)

The Tayport Formation grades laterally into extensive coastal-plain associations of the Tournaisian Cementstone Formation. To the south of the study area (onshore Northumberland Basin and Craven Basin), Tournaisian platform carbonates were deposited on isolated highs (Lyne Formation of the Border Group), much akin to what is seen in the onshore Netherlands (Reijmer *et al.* 2017; Vis *et al.* 2025). It is essentially unknown what deposits are present between the Cementstone facies belt and those (isolated) carbonate build-ups during the Tournaisian. The characteristic Tournaisian Cementstone facies is characterized by cyclic siltstones, cementstones and evaporites deposited in a coastal-plain to marginal-marine semi-arid setting with generally low water tables. The cementstones typically occur in beds up to 1 m thick and were probably deposited in saline lagoons (Andrews *et al.* 1991). Abundant well-drained pedotypes (Kearsey *et al.* 2016) support the inference of subaerial conditions. Episodically more pronounced marine conditions occurred in UK Quadrants 41–44 and possibly in the Dutch offshore (Quadrants E06 and E02), testified to by the presence of thicker limestone beds.

Samples for this unit were only available from the two outcrop sections of Burnmouth and Pease Bay. Although 24 wells penetrate the Tayport and Cementstone strata in the study area, no cores were available/studied. Hence, lithological and stratigraphic information are based on wireline-log patterns and cuttings descriptions. The log interpretation of the top of the Cementstone Formation is very robust, owing to its very distinct log response (see supplementary appendices A–D of of Bouroullec *et al.* 2025*b*).

The organofacies assemblages, as well as the identified vegetation pattern (Fig. 8), show that the samples were deposited in a fully oxygenated environment (alluvial to coastal plains). The dominant vegetation consists of ferns, typically growing on clastic substrates along rivers and in overbank settings. Arboreal lycopsids are virtually absent, indicating that there were no extended swamps/mires (i.e. no elevated water tables) or organic material of local origin. This picture is probably related to the strongly monsoonal and seasonally arid conditions typical for the equatorial palaeolatitude of the study area during the Tournaisian (see also Falcon-Lang 1999).

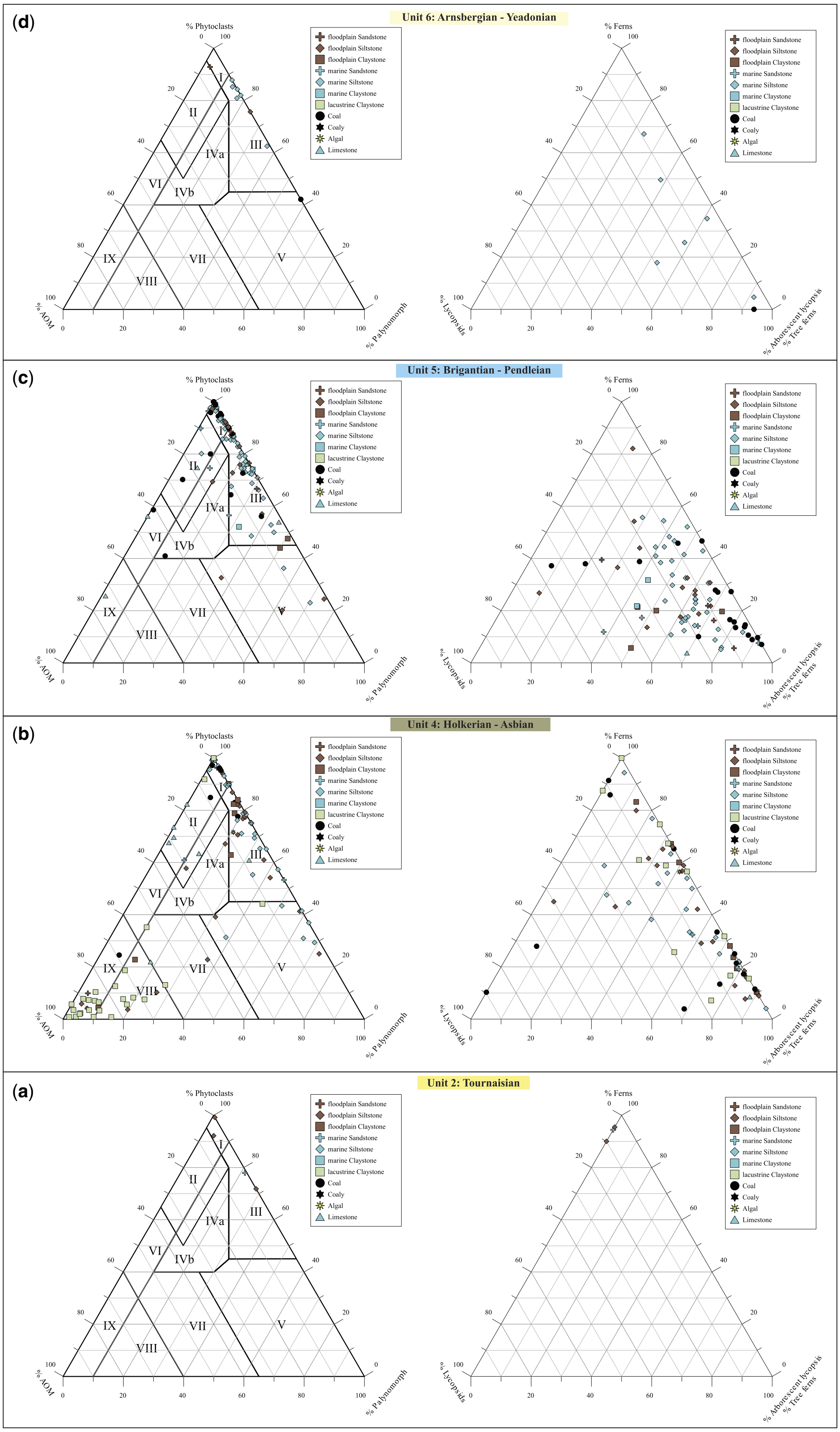

Fig. 8. Palynological and organofacies ternary diagrams for selected Early Carboniferous time slices: (**a**) Tournaisian/Interval 2; (**b**) late Holkerian–Asbian/Interval 4; (**c**) Brigantian–Pendleian/Interval 5; and (**d**) the Arnsbergian–Yeadonian/Interval 6. The datapoints comprise data from both onshore outcrop sections and offshore core sections. Datapoints are categorized according to lithofacies, as identified during core and outcrop measured sections. On the left-hand side of this figure, the axes display the relative abundance of AOM, phytoclasts and palynomorphs. These relative proportions are interpreted following Tyson (1995) into nine depositional environments (Table 4). On the right-hand side of the figure, ternary diagrams show the relative distribution of three vegetation components (see the Supplementary Material): ferns representing pioneer-stage, non-flooded habitats; lycopsids representing nutrient-poor, ever-wet habitats; arborescent lycopsids and tree ferns representing humid wetland to wetland-margin habitats.

Table 4. Environmental classification scheme using the relative abundance distribution of organofacies groups, adapted after Tyson (1995)

No.	Description
I	Highly proximal shelf or basin
II	Marginal dysoxic to anoxic basin
III	Heterolithic oxic shelf ('proximal shelf')
IV	Shelf to basin transition
V	Mud-dominated oxic shelf ('distal shelf')
VI	Proximal suboxic to anoxic shelf
VII	Distal dysoxic to anoxic shelf
VIII	Distal dysoxic to oxic shelf
IX	Distal suboxic to anoxic shelf, carbonatic shelf, restricted marine (proximal), lagoonal to lacustrine

Early Visean/Chadian–Holkerian (Unit 3)

The stratigraphic synthesis has shown that the oldest Stage of the Visean is typically not present, giving rise to the BVU. By Arundian times, a major delta system extended across the region. A major, braided fluvial system, probably originating in the Caledonian Mountains far to the NE, spread coarse-grained sandstone in stacked, multistorey sheets southwards (Morton *et al.* 2001). This system led to deposition of the Fell Sandstone Formation. In the onshore Northumberland Basin, sandstone sheets are intercalated with marine siltstones, and the Fell Sandstone Formation progrades southwestwards (Turner *et al.* 1997). In the south, the time-equivalent rocks are the interbedded sandstone and mudstone of the Cleveland group A, and possibly the mudstone-dominated Cleveland group B. The sandstone units probably represent the distal facies of the Fell Sandstone Formation.

Chronostratigraphic Unit 3 is mainly represented by the Fell Sandstone Formation, identified onshore and offshore. The base of the formation is erosive and appears to be diachronous; the top is defined by the top of the last thick sandstone interval before the typical mudstone, sandstone and coal succession of the Scremerston Formation. This boundary appears to be a gradual and diachronous transition. An example includes the Fell Sandstone–Scremerston Formation transition in the UK Quadrant 41 area. In well 41/10-1, for instance, the Fell Sandstone, as a sand-rich unit, is extremely thin. The overlying succession is consequently included in the Scremerston Formation. However, it is in essence simply a sand-poor lateral facies equivalent to the Fell Sandstone Formation (see fig. 26 in Kearsey *et al.* 2015). These differences may be explained by changes to the channel fairway position and/or by changes in accommodation rates, both in a proximal–distal sense and a lateral sense. Along the same line of reasoning, Fell Sandstone Formation-equivalent strata can be interpreted in the basal 600 m of the greatly thickened Seal Sands No. 1 Borehole. However, it is much more heterolithic than in its 'classic' sand-rich expression.

Owing to the project's focus on source-rock prolific intervals, no samples from Unit 3 were analysed palynologically. Nevertheless, the top of Unit 3 is defined by a major floral turnover event recorded widely in palynological records, midway through the Holkerian, probably related to a change in climate (top V2/TS zone). This turnover marks the first occurrence of *Schulzospora*, enigmatic saccate spores that are thought to be linked to modern-day cycads. The appearance of these arborescent forms may suggest a regional increase in humidity. This level also marks the extinction of numerous quantitatively significant Tournaisian and early Visean taxa (*Verrucosisporites nitidus*, *Auroraspora macra* and *Crassispora trychera*).

To the north of the study area, in the Witch Ground Graben (in UK Quadrants 14 and 15), Whitbread and Kearsey (2016) reported the first development of the Firth Coal Formation facies by Chadian–Arundian times. No evidence for such an old age for coal-bearing strata could be found in the available legacy data. We therefore assert that the onset of deposition of the Firth Coal Formation is coeval with the Scremerston Formation during the Holkerian (Fig. 7).

No major sandstone deposition has been recorded in the northern part of the study area (except in wells 26/07-1 and 21/02-1), the main area of Fell Sandstone Formation distribution being located around the Mid North Sea High (MNSH) (e.g. wells 38/16-1, 38/24-1, 43/05-1 and 44/02-1) and in the Tweed and Northumberland basins (e.g. Howell *et al.* 2022). Further south, shale-dominated successions of the Cleveland group (offshore) and Craven Group (Pennine Basin) have been reported (Maynard and Dunay 1999).

The Fell Sandstone Formation represents a major fluvial system that traversed the study area with sources in the Caledonian highlands to the north. The absence of similar sandstone deposits in UK Quadrant 20 and further north could be caused by sediment bypass. According to recent studies by Howell *et al.* (2019, 2022), the distribution of sandstone facies was subjected strongly to structural control. The later onset of sand deposition further south is in line with the NE–SW direction of sediment transport. In UK Quadrants 42–44, coal deposits with a classic Type III kerogen occasionally accumulated in overbank environments (Fig. 10).

Middle Visean/Holkerian Asbian (Unit 4)

Late Asbian times saw the first development of the fluvio-deltaic Yoredale facies across the region. Glacioeustatic fluctuations affected the delta-top and delta-plain environments by episodic transgressions, establishing shallow carbonate platform conditions followed by clastic sediment infilling accommodation space, resulting in terrestrialization and the development of coal mires (e.g. Wright and Vanstone 2001). The Scremerston Formation is used to reflect facies associations in which the limestone part of the cycle is generally short-lived and thin to absent. In contrast, towards the south and east, limestones are thicker and more consistent (see e.g. E06-01 in The Netherlands). In the meantime, 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. More southerly, UK onshore blocks finally became submerged during Asbian times, leading to carbonate platform deposition. A more mudstone-dominated succession of Cleveland group C is encountered to the south in the Cleveland Basin. These basins are likely to have experienced an extensional history and, by implication, a transtensional component implied by localized depocentres such as that documented by the Seal Sands 1 Borehole and wells south of the Elbow Spit High (Dutch well E06-01: see also Bouroullec *et al.* 2025*b*).

In terms of lithostratigraphy, Unit 4 includes the Scremerston Formation and onshore equivalents the Gullane Formation and Scremerston Coal Member of the Tyne Limestone Formation, parts of the Firth Coal Formation, the Asbian interval of the West Lothian Oil-Shale Formation, and the Cleveland group B and parts of C (Fig. 7). A wide array of kerogen types of variable quality is recorded in this unit, in line with the wide range of depositional environments recognizable in the successions. Hence, the different kerogen types are discussed here according to inferred depositional environment.

The samples from lacustrine environments were taken from the South Queensferry section and are part of the Asbian of the West

Lothian Oil-Shale Formation. The formation was deposited in the Midland Valley Basin complex, a series of north–south-trending tectonic troughs believed to have been land-locked to the north, south and west, with a partially restricted connection to marine environments to the east (e.g. Jones 2005; Monaghan *et al.* 2024). When totally cut-off from the sea, a series of standing water bodies formed, referred to as Lake Cadell. This led to a complex interaction between freshwater lacustrine, transitional lagoonal and episodical marine conditions (Jones 2005). The formation consists of a succession of oil shales, ostracod-rich limestones, siderite-bearing claystones and siltstones, fluviodeltaic sandstones, and calcareous mudstones deposited in freshwater lacustrine, transitional lagoonal and transitional marine conditions. In the context of this project, mainly kerogen-rich claystones of lacustrine origin were sampled. Palynological analyses show that the samples are dominated by *Botryococcus*, which is consistent with the prevalence of freshwater conditions. The organofacies plot shows an abundance of AOM in the samples (Fig. 8). In association with these lacustrine/lagoonal samples, we recorded an increased abundance of the *Rugospora* group of spores. We interpret this increase in spore abundance as indicating local lake-fringing pioneer vegetation. Overall, the vegetation composition in lacustrine samples is highly variable, ranging from fern-dominated to arborescent lycopsid-dominated (Fig. 8). This variation is attributed to the variable influx of riverine material into the lake system, thus capturing a relatively variable local and hinterland signal.

The floodplain environment is defined as one in which all sediments are deposited in alluvial channel and overbank environments and lagoonal settings. The sediments deposited in the floodplain environment consist of sandstones deposited mainly in channels, and claystones and siltstones of overbank facies associations that have undergone pedogenic processes, as well as sediments deposited in a lagoonal setting that have not undergone pedogenic processes. In terms of organofacies association, within the floodplain environment, there is indeed substantial scatter. Whereas some samples are dominated by AOM and plot within the lagoonal domain (Doupster Oil Shale from the Spittal section: Fig. 4), other samples are phytoclast-dominated, pointing towards a more fluvial-derived sediment source. The vegetation components are rather well mixed in most of the Asbian floodplain lithofacies samples. However, non-arborescent lycopsids appear underrepresented. This possibly indicates a more regional ecological reorganization towards more arborescent-dominated climax vegetation types, driven by a higher degree of humidity, complemented by the fluvial influx of ferns.

Numerous Asbian coal samples were sampled, both from offshore cores and outcrop sections. In terms of organofacies, the coals are dominated by phytoclasts. This is quite typical for humic coals, given their origination from peat mires. Only one coal sample was dominated by AOM (Fig. 8). In terms of vegetation composition, coal samples tend to be dominated by lycopsids, in particular the arborescent forms of the *Lycospora* (Fig. 8). This is related to the development of lowland swamp areas that were colonized by humidity-prone larger forms. Ferns are typically underrepresented in most of the coals. In coals with a reduced hydrogen index (HI) (see Fig. 9), the elevated abundance of ferns may point towards to an enrichment of 'inert' transported kerogen, leading to a reduced HI. Significant abundance of potentially hydrogen-prone palynomorphs such as *Botryococcus* is not recorded in any of the sampled coals.

One of the research questions of the Paleo-Five Project was to establish to what extent marine lithofacies of the Yoredale cycles contribute to enhanced source-rock potential. This led us to explore for indications of anoxic conditions and/or stratification. An important observation is that no AOM-enriched organofacies associations were encountered in marine siltstones and claystones. All of the marine sediments were clearly deposited in an oxic, at most dysoxic, environment where only oxidized organic matter was preserved. This is confirmed by palynological associations that lack significant amounts of AOM or palynological indicators for a stratified water column, such as prasinophyte algae and/or acritarchs. Most of the organic matter in the marine realm is in effect of terrigenous origin (Fig. 8). By analogy to the floodplain associations, the vegetation composition is again rather well mixed, and non-arborescent lycopsids appear underrepresented, which we ascribe to the development of arborescent-dominated climax vegetation types.

Overall, the Asbian is marked by a conspicuous change in vegetation composition, compared to the Tournaisian and early Visean. First, the arborescent lycopsids indicated by the *Lycospora* Group

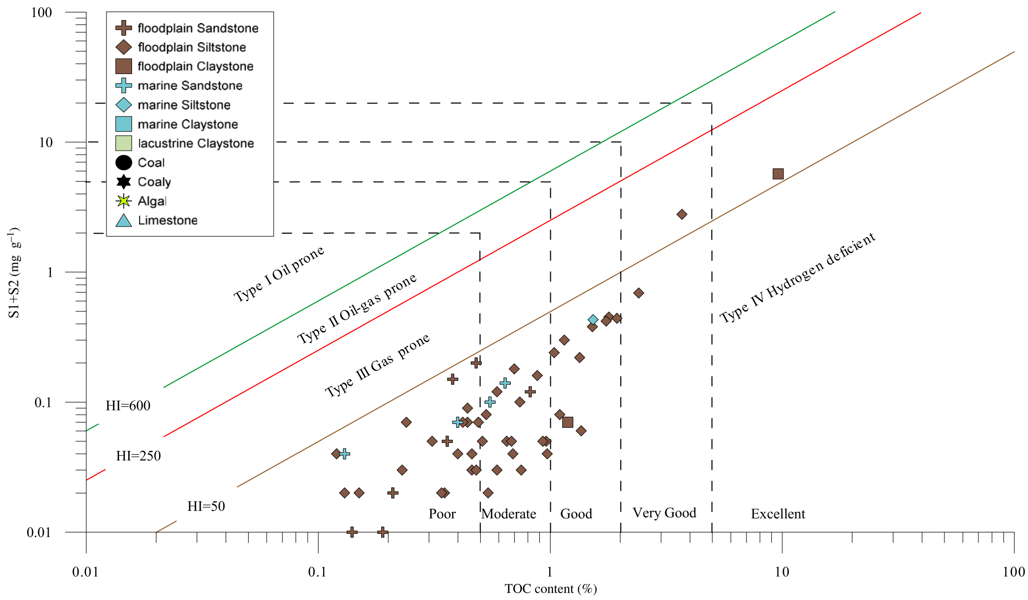

Fig. 9. S1 + S2 peak (in mg HC/gTOC) v. TOC content for the samples from the Tournaisian (Unit 2). The symbols indicate the recorded lithology and inferred depositional environment of the samples. The sum of the S1 and S2 peaks represents the potential for hydrocarbon generation for higher maturity samples. Plotted against TOC, this gives an indication of organic-matter type and quality.

increase in abundance dramatically. In addition, *Schulzospora* becomes a quantitatively important taxon. This saccate form is ascribed to be linked to modern-day cycads and is thus also interpreted as arboreal. Vegetation associations also become very cyclic, probably in relation to persistent base-level variations that drive vegetation cycles between pioneer-stage fern-cormose lycopsid stages that grade into inland swamp climax stages boasting arboreal swamp forest elements. Sphenopsids are a relatively minor component, which suggests that extensive mangrove-like belts were not developed in the region during the Asbian.

Brigantian–Arnsbergian (Unit 5)

At the start of the Brigantian, Yoredale fluvio-deltaic sediments continued to be deposited. Marine limestones overall reached 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). 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 limestone were deposited (see the Cleveland group in Fig. 7) (see also Kearsey *et al.* 2019), suggesting that the delta had prograded southwards into the Cleveland Basin. Brigantian Yoredale facies are encountered as far eastward as Denmark (Gert-2 well). However, further northwards (e.g. in UK Quadrants 14, 15, 20 and 21) siltstone-dominated terrestrial successions with abundant coals continued through this period (Fig. 7), thus displaying this north–south-orientated nature of the Yoredale delta system.

The Yoredale system continued to be deposited through the Pendleian and Arnsbergian (Fig. 7). Over time, fluvial, fine- to medium-grained sandstones became progressively more significant within the Yoredale succession (Kearsey *et al.* 2019). In the Cleveland Basin, a package of mudstones and silty mudstones was deposited. High GR values characterizing the uppermost Brigantian–Pendleian Upper Bowland Shales show this unit to be a consistent marker across wells penetrating the group south of the MNSH (e.g. Areas 16 and 17: Fig. 7). In The Netherlands, similar GR-rich shales are also recorded in some wells; however, not clearly within the study area (see also supplementary appendices A and D of Bouroullec *et al.* 2025*b*). According to Vis *et al.* (2025), an early Namurian sea-level rise caused an incipient Variscan foreland basin to be initially filled with basinal shales and turbidites. In particular, areas that did not receive incipient southerly-sourced sediments, thus away from Dinantian highs, were susceptible to deposition of the bituminous Geverik shales. This suggests that the Geverik shales and the Upper Bowland Shales, albeit more or less time equivalent, were different features, partly because of a differentiation in the sediment sourcing that developed between the central-southern Netherlands and the UK area south of the MNSH. Within Unit 5, a very wide array of kerogen types and quality are encountered, in line with the broad range of identified depositional environments and facies associations (Fig. 8).

From a lithostratigraphic point of view, coals occur in the Firth Coal Formation in the northern UK offshore quadrants and in the Yoredale Formation in the southern and central part of the study area, and in the correlative onshore formations, namely the Alston and Stainmore formations. The vegetation pattern identified from coals is very similar to that inferred from coals of Unit 4. In terms of organofacies, coals are dominated by phytoclasts. Higher proportions of palynomorphs develop in offshore oxic mud-dominated settings, whereas anoxic/dysoxic and/or strongly stratified marine and lacustrine water bodies are dominated by AOM. The majority of coals is dominated by arborescent lycopsids. This is related to the development of lowland swamps populated by humidity-prone larger forms. Ferns are typically under-represented in most coals. A significant abundance of potentially hydrogen-prone palynomorphs such as *Botryococcus* is practically absent in these coals.

Floodplain mudstones show no marked difference from the siltstone facies. No organic-rich lagoonal or lacustrine deposits were encountered in this unit. The vegetation analysis of the Unit 5 floodplain sediments shows a less fluctuating pattern compared to Unit 4. This is partly related to the absence of intercalated lagoonal facies associations. No fern-dominated intervals were identified, suggesting that the depositional environment remained relatively wet with high water tables.

The marine sediments were deposited in an oxic, at most dysoxic, environment. This is also shown by palynological associations lacking significant amounts of AOM or algae that indicate stratification, such as prasinophyte algae or acritarchs. However, the assemblage shows a clear marine signal, as corroborated by facies analysis. Pyrite recognized in the deposits is related to later, post-depositional development of anoxic conditions within the unconsolidated sediment, and had no influence on the composition of the organic material. Only marine limestones show an elevated abundance of AOM. This is considered merely an effect of the absence of other kerogen sources and probably not of anoxia. The amount of preserved organic material is very low (TOC content <1%) and shows a clear Type IV kerogen signal. It can therefore be concluded that even though sampling was mainly focused on dark, seemingly organic-rich, marine siltstones and limestones, we see no indication of a marine anoxic environment within Unit 5.

According to facies interpretations, depositional processes in the basin become progressively more marine-influenced in the Brigantian compared to the Asbian. This is exemplified by more frequent and thicker limestones, and by more expanded offshore siltstones and claystones. In relation to the above, the vegetation composition as deduced from palynological analyses shows an increase in arboreal elements (arboreal lycopsids and tree ferns) at the expense of pteridophyte fern spores (see Fig. 8). The latter is likely to be related to a general increase in humidity and more elevated water tables on the extensive coastal plains, as represented by (the Brigantian part of) the Yoredale Formation. This may have influenced the preservation of organic matter in floodplain deposits through a reduction of clastic dilution during the Brigantian. The higher water tables may also have played a role by enhancing organic-matter preservation during early post-depositional stages. This large-scale environmental change may have contributed to the overall increase in Type III kerogen content in the floodplain deposits.

In terms of generalized vegetation trends, the base of the Brigantian is characterized by a relative increase in non-arborescent lycopsids of the *Densosporites* complex. In addition, the cyclicity between arborescent and non-arborescent forms seems to become less pronounced and, consequently, floral associations appear to have become more stable. This situation continues into the Pendleian. Overall, this implies the development of a more developed climax vegetation, typically for a coastal-plain environment.

Arnsbergian–Yeadonian (Upper Unit 5 and Unit 6)

By Arnsbergian times, a northward retrogradation of the finer-grained marine Cleveland group E is noted up to the northern part of Quadrants 41 and 42 in the UK (Area 12 in Fig. 7), and Blocks A14, A16 and A17 in The Netherlands (Area 13 in Fig. 7). Subsequently, most of Unit 6 comprises the Millstone Grit Formation in both onshore and offshore domains. Samples from these formations are mainly from the Howick outcrop and the UK offshore wells 43/19-2 and 41/15-1. In contrast to the boundary between Unit 5 and Unit 6 shown in Figure 7, located at the top of the Arnsbergian, the lower boundary in this overview is set at the top of the Pendleian. This choice was made to better capture the synchronous deposition of the Millstone Grit and Cleveland group/Upper Bowland Shales succession in the south of the study area (southern quadrants 41 and 42). The Millstone Grit Formation is described as cyclic deposits of sandstones, mudstones, associated coal strata and pedogenized fine clastics. Palynofacies and vegetation analyses suggest a similar depositional environment as the underlying units of deposition on a proximal oxidizing environment, with vegetation dominated by arborescent lycopsids (Fig. 8). The marine facies do not show any significant indications of stratification.

Trends in vegetation development

From the palynological associations as a whole, a consistent dominance of terrestrial elements and overall lack of marine palynomorphs are evident. The only exceptions are some of the lacustrine–lagoonal intercalations recorded in the upper Asbian in the sections at Spittal and Cove, which bear large numbers of the colonial alga *Botryococcus*. The occasional occurrence of scolecodont fragments in the Asbian and younger strata illustrates the episodical persistence of marine conditions.

The sporomorph-based vegetational groups display distinct variations over the course of the Early Carboniferous (Fig. 8). More consistent reorganizations, variations and regime shifts are summarized below.

Although based on a limited number of samples, the Tournaisian–Holkerian samples are distinct from Asbian and younger samples. Ferns and non-arborescent cormose lycopsids are the dominant vegetation type. The few arborescent components are sphenopsids (related to calamites) and the arborescent lycopsids linked to the *Crassispora* group of spores. We speculate that this Tournaisian–early Visean vegetation in the region is related to lower water-table levels and relative aridity, compared to the younger samples. It thus seems that the Tournaisian was warm and relatively arid in the study area. It has recently been suggested that a period of potential cooling and possible glaciation occurred in the middle–late Tournaisian (Buggisch *et al*. 2008; Lakin *et al.* 2016). We hypothesize that the BVU may be related to an associated sea-level fall.

The Asbian (Unit 4 and lower Unit 5) marks a conspicuous change in vegetation composition compared to the Tournaisian and early Visean (Fig. 8). First, the arborescent lycopsids indicated by the *Lycospora* increase in abundance dramatically. In addition, *Schulzospora* becomes a quantitatively important taxon. This (pseudo)saccate form is linked to modern-day cycads, and is thus considered a tree-size element. From the Asbian onwards, the dominant vegetation types vary cyclically, probably in relation to base-level variations that drive vegetation cycles between pioneer-stage fern-non-arborescent lycopsid stages that grade into swamp climax stages containing abundant arboreal elements. Superimposed on these cycles, a relatively humid greenhouse-state climate persisted. This is in line with the observation that the forcing ice sheets were likely restricted to upland environments (ice caps; Fielding *et al.* 2008). Note that sphenopsids remain a relatively minor vegetation component, suggesting that extensive mangrove-like vegetation belts, such as those seen in the Westphalian, were not developed in the region during the Asbian.

At the base of the Brigantian, a relative increase in non-arborescent lycopsids of the *Densosporites* complex can be observed. In addition, the cyclicity between arborescent and non-arborescent forms seems to become less pronounced, and, consequently, the vegetation appears have become more equitable (Fig. 8). This situation continued into the Pendleian. Overall, this implies the development of a more developed climax vegetation, typically for extensive coastal-plain environments. This may be linked to a cooler and glacioeustatic stable regime that was established by that time (Rygel *et al.* 2008).

The next vegetation shift is recorded by Arnsbergian times. Non-arborescent lycopsids are now prominent and cordaite gymnosperms are recorded in small abundance. The latter is an evolutionary phenomenon, with the rise of this plant group by that time (Gomankov 2009 and references therein). Despite the occurrence of these tree-posture plants, it seems that the swamp forests developed during the Asbian–Pendleian have diminished, probably as a consequence of increased cooling, increased clastic supply and/or seasonal aridity, linked to a further intensification of glacioeustatic activity by that time (Rygel *et al.* 2008).

The above leads to conclude that the arid monsoonal conditions characterizing much of the Devonian and Tournaisian waned by the onset of the Visean. From the late Visean (late Asbian–Brigantian) onwards, our palynological data illustrate that although glacioeustatic changes may have become increasingly important, warm and subhumid to humid climate conditions persisted through the study area. Regional climate may thus be considered as more persistent over longer timescales than often assumed. Part of this may be explained by the fact that major climate variability was buffered by the peri-equatorial position and by the relative proximity to tropical Palaeo-Tethys Ocean, which may have been an important regional moisture source.

Source-rock character

One of the goals of the Paleo-Five Project was to provide an overview of the organic content of the studied deposits, with the aim of assessing the source-rock potential of the Lower Carboniferous. Whilst disclosing all details warrants a separate publication, an effort is made here to describe the main organic-content characteristics of this unique dataset. This is achieved by discussing TOC content and Rock-Eval results in stratigraphic order, from older to younger, and comparing these to lithofacies observations from core and outcrop samples.

Devonian (Unit 1)

The floodplain sandstone samples from Unit 1, the Buchan and Tayport formations, in the study area have very low organic matter content and practically no hydrocarbon generation potential. North of the study area in UK offshore Quadrants 5–14, legacy data from the Eday Group and the Orcadia Formation show excellent Type I and II source-rock characteristics in lacustrine deposits (Whitbread and Kearsey 2016). The local equivalents of these units are the marine carbonates of the Kyle Group, which were not sampled for this study.

Tournaisian (Unit 2)

The samples from Unit 2 show an overall low organic-matter content of less than 2%, with some outliers (Fig. 9). In addition to the low total organic content, the results of the Rock-Eval analysis (S1 and S2 peaks) show an even lower potential for hydrocarbons, therefore characterizing the organic-matter fraction as a classic Type IV with oxidized organic matter of terrigenous origin. No evidence for coal has been found, nor do vegetation patterns suggest any proximity of swamps or mires. While it is possible that short-lived swamps and floodplain ponds developed in this system, their temporal and areal extent would have been very limited, and any organic matter accumulated probably degraded rapidly.

Early Visean/Chadian–Holkerian (Unit 3)

No samples of the Fell Sandstone Formation, Unit 3, were analysed in the context of this study. Legacy data do, however, show some samples with very high organic matter content and kerogen Type

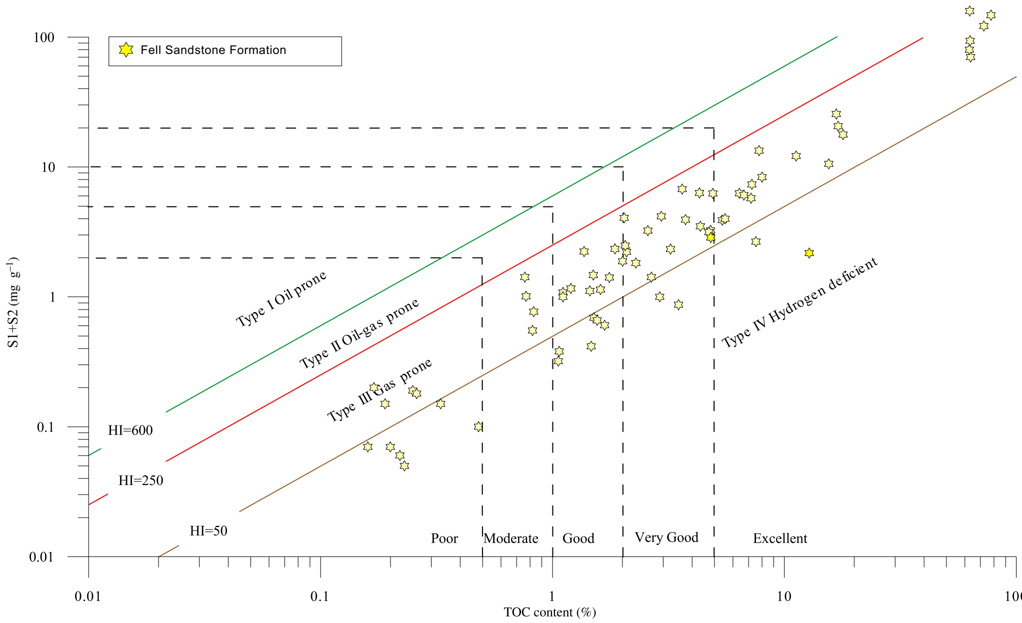

Fig. 10. S1 + S2 peak (in mgHC g^{-1} TOC) v. TOC content for the samples from the early Visean (Chadian–Holkerian). Only legacy data were available, without detailed lithological information. Therefore, the values are reported against lithostratigraphic assignment (Fell Sandstone Formation) The sum of the S1 and S2 peaks represents the potential for hydrocarbon generation for higher maturity samples. Plotted against TOC content, this gives an indication of organic-matter type and quality.

III characteristics, suggesting the presence of coals in the unit (Fig. 10).

Middle Visean/Holkerian–Asbian (Unit 4)

The samples from Unit 4 show a very large variety of source-rock quality and type (Fig. 11). The analysed lagoonal–lacustrine samples (lacustrine, West Lothian Oil-Shale Formation: shown as light green squares in Fig. 11) as well as some samples deposited in a floodplain environment (lagoonal, e.g. Doupster Oil-Shale bed in Spittal: shown as brown diamonds in Fig. 11) are very hydrogen and TOC rich, and show a classic Type I kerogen composition. The lagoonal deposits occur in delta-plain settings that may originally have been located at a significant distance from principal drainage pathways, favouring the establishment of sediment-starved lagoons featuring excellent oil-generating properties, but which are of very limited thickness and extent. The coals (shown as black circles in Fig. 11) in Unit 4 have a higher HI

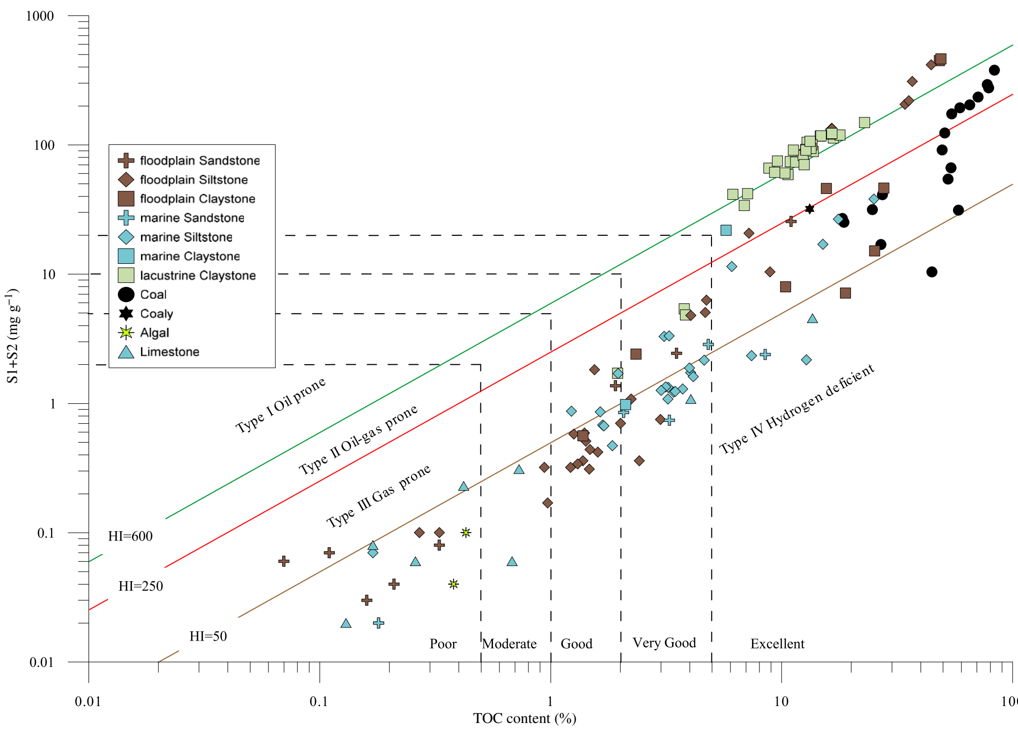

Fig. 11. S1 + S2 peak (in mgHC g^{-1} TOC) v. TOC content for the samples from the upper Holkerian to the Asbian (Unit 4). The symbols indicate the recorded lithology and inferred depositional environment of the samples. The sum of the S1 and S2 peaks represents the potential for hydrocarbon generation for higher maturity samples. Plotted against TOC content, this gives an indication of organic-matter type and quality.

(>300 mg g^{-1} TOC content) compared to the coals of Unit 3 and almost all plot in the area of Type II/III kerogen. They also show slightly elevated amounts of AOM. Legacy data show a similar character for the coals of the Firth Coal Formation. The organic content in floodplain sandstones and claystones (shown as brown crosses and squares in Fig. 11) varies and can be as high as 10% TOC content. This is probably related to dispersed, coal fragments in channel-fill deposits, which is in line with kerogen Type III. The marine samples, even though some show elevated TOC contents of 2–5%, can be classified as Type IV source rocks with mostly inert/oxidized organic matter and very little hydrocarbon generation potential.

Brigantian–Pendleian (Unit 5)

The samples of Unit 5 show a very similar trend to samples of Unit 4 except for the absence of the lagoonal–lacustrine Type I oil shales (Fig. 12). Overall, the marine sandstones, siltstones and claystones show elevated organic matter contents; however, according to organofacies analysis, they were still deposited in an oxygenated environment. The available kerogen would be classified as a Type IV, inert kerogen. In the south of the study area, Unit 5 also includes the marine Upper Bowland Shale of the Cleveland group. For this interval, only legacy data were available, which show good Type II marine source-rock potential in the onshore Cleveland Basin. The available offshore samples are overmature and therefore cannot give a good indication of their source-rock potential.

Arnsbergian–Yeadonian (Unit 6)

Only a few samples were analysed for Unit 6 (Fig. 13). The marine and floodplain samples again show deposition in a mainly oxygenated setting with little source-rock potential. The coals and coaly sandstones show classic Type III kerogen characteristics, with lower HI values compared to the coals of Unit 4 and Unit 5.

Although this study does not explicitly aims to provide insights into the maturity history of the area, it is clear that the highest T_{max} values of Visean and younger rocks (>480°C) are recorded in the south of the study area (Areas 16 and 17; see also Supplementary Appendix G). Many of the above-mentioned coal and lacustrine–lagoonal shale units occur in the subsurface within the oil and gas generation windows. The reader is referred to Monaghan *et al.* (2017) for a more elaborate discussion, including basic modelling of the UK counterparts of the investigated time interval.

Stratigraphic and tectonostratigraphic synthesis

This discussion is closely linked to the research presented in the companion paper by Bouroullec *et al.* (2025*b*, notably fig. 8). From the Tournaisian to the mid-Chokierian, a large long-term retrogradational trend can be seen. A major unconformity is found at the base of the Visean and numerous transgressive phases have occurred since the middle Asbian. At the base of this sequence (i.e. thus in the mid-Asbian), conspicuous lacustrine–lagoonal intercalations are recorded in a number of different tectonic elements. During the Asbian–Arnsbergian, the glacioeustatic variation became predominant with multiple Yoredale cycles stacking across a relatively flat landscape where pre-existing topographical highs were progressively buried (see Bouroullec *et al.* 2025*b*, fig. 16). The retrogradational trend is followed by the mid-Namurian Unconformity of late Chokierian–lowermost Alportian age, followed by progradation of the Millstone Grit depositional system, highlighted by the more than 150–200 km southward shift of the coastline during the Alportian.

A conceptual cross-section (Fig. 14) was constructed to better visualize the regional tectonostratigraphic framework of the Lower Carboniferous in the study area provided by Bouroullec *et al.* (2025*b*). Representing the geological complexity and heterogeneity of the Lower Carboniferous of such a large area

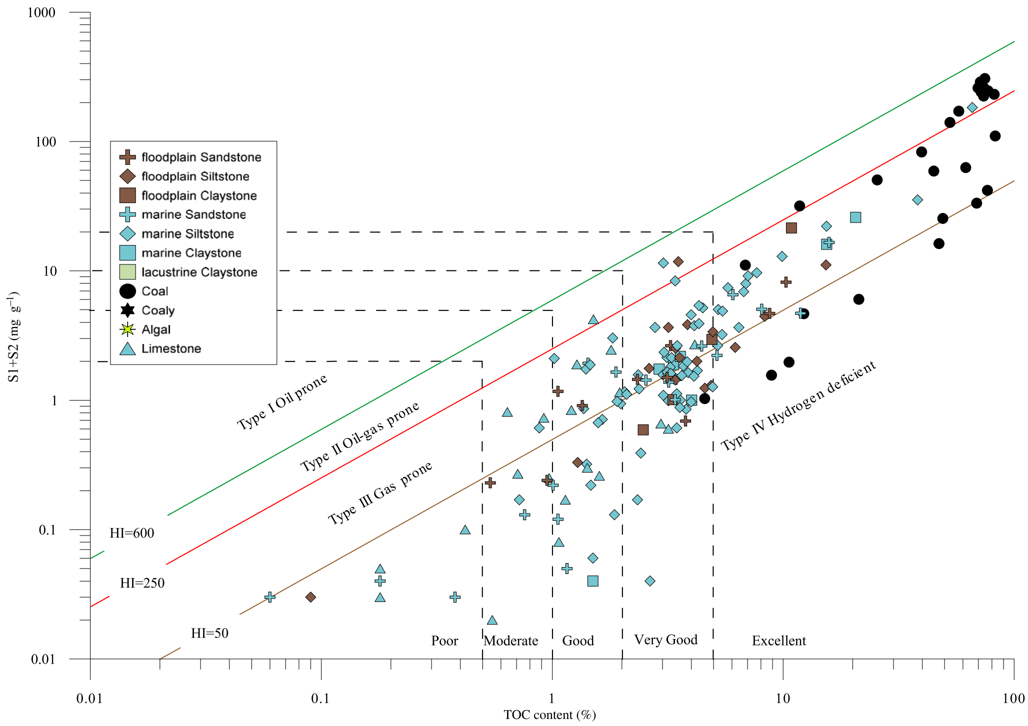

Fig. 12. S1 + S2 peak (in mgHC g^{-1} TOC) v. TOC content for the samples from the Brigantian to the Pendleian. The symbols indicate the recorded lithology and inferred depositional environment of the samples. The sum of the S1 and S2 peaks represents the potential for hydrocarbon generation for higher maturity samples. Plotted against TOC content, this gives an indication of organic-matter type and quality.

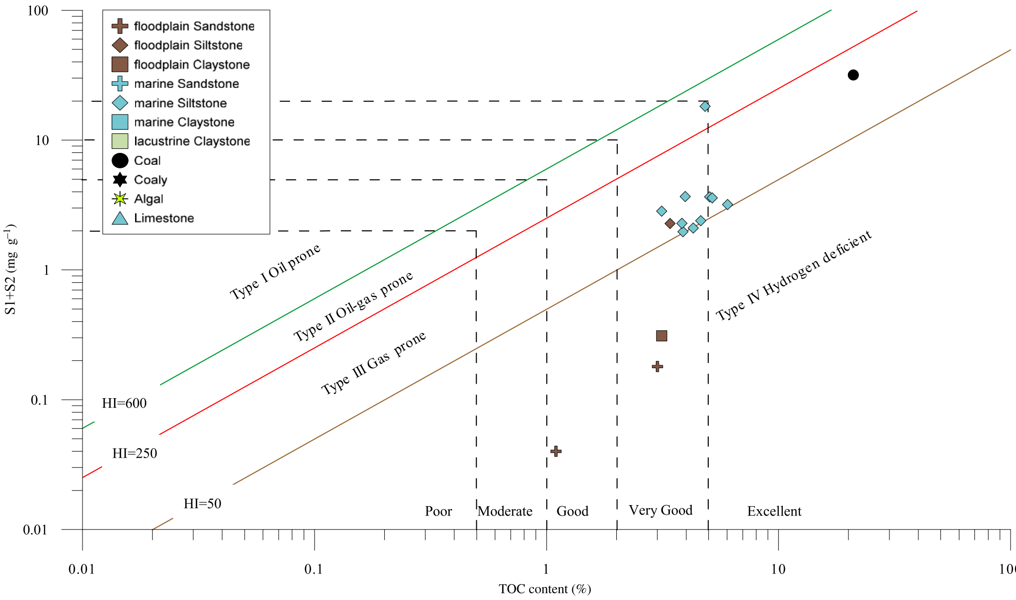

Fig. 13. S1 + S2 peak (in mgHC g^{-1} TOC) v. TOC for the samples from the Arnsbergian to the Yeadonian. The symbols indicate the recorded lithology and inferred depositional environment of the samples. The sum of the S1 and S2 peaks represents the potential for hydrocarbon generation for higher maturity samples. Plotted against TOC content, this gives an indication of organic-matter type and quality.

using a single representative cross-section is challenging. Parts of the study area underwent a structural evolution that locally may differ from the proposed cross-section (Fig. 14). Below is a description of the steps taken to build this conceptual tectonostratigraphic model, based on seismic and well data, and observations gathered from various parts of the study (including stratigraphic analysis, outcrop information, seismic mapping, structural analyses and palaeogeographical mapping).

A SSW–NNE-trending cross-section was selected to better represent the tectonostratigraphic framework, running perpendicular to the main structural elements (e.g. the Central North Sea High (CNSH) and the MNSH, and the Coffee Soil Fault System of

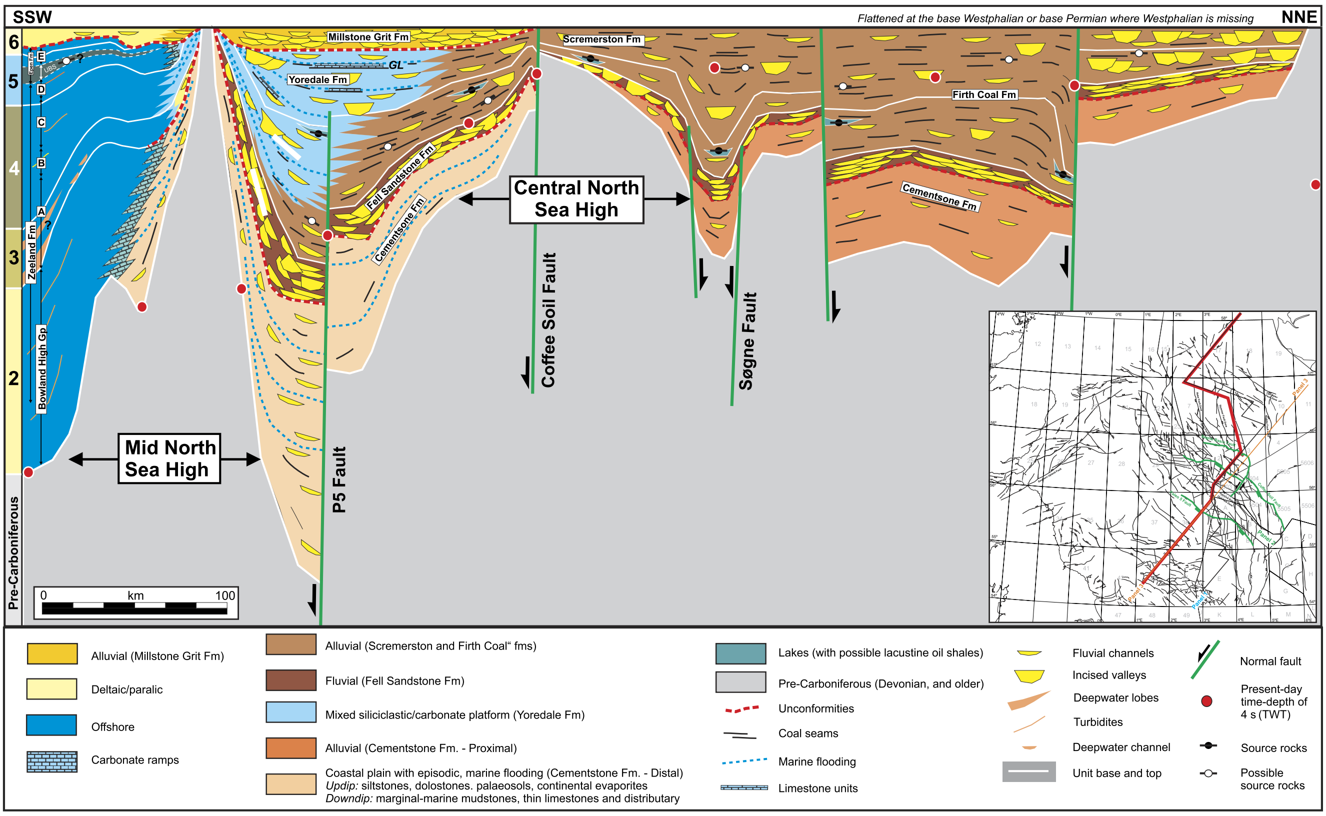

Fig. 14. Tectonostratigraphic regional cross-section in the Central and Southern North Sea, from the Norwegian sector to the Dutch and UK sectors. See the text for comments. GL, Great Limestone; A–E refers to the Cleveland groups A–E. The red-coloured circles represent the present time depth of 4 s (two-way time (TWT)) as a reference. Note that no vertical scale is shown as the section was constructed from a time–depth section. This section also displays specific stratigraphic elements such as fluvial-channel fills, incised-valley fills, lacustrine deposits, coals seams, noticeable limestone units (e.g. Great Limestone), presumed deep-water elements such as channels and lobes, and syndepositional faults.

Bouroullec *et al.* 2025*b*), as well as to the main palaeocoastline trends (WNW–ESE). This cross-section was also positioned to comprise regionally important Early Carboniferous syndepositional faults, such as the Coffee Soil and P5 faults as perpendicular as possible (Bouroullec *et al.* 2025*b*, figs 16 and 17). For more information on the palaeogeography, palaeohighs and synsedimentary faults, refer to Bouroullec *et al.* (2025*b*).

Two of the regional seismic panels from Bouroullec *et al.* (2025*b*, supplementary appendices F and G) were merged. Several additional 2D seismic lines from the NSR survey in the Norwegian offshore were also use to link both seismic panels 2 and 3 from Bouroullec *et al.* (2025*b*, fig. 14).

The new combined section was flattened at the base of the Westphalian level or base Permian where the Westphalian section is missing in Norway. Devono-Carboniferous units were added underneath the Central Graben, based on evidence that the Coffee Soil Fault and Søgne Basin Fault are likely to have been active during the Devonian and Carboniferous. Carboniferous strata eroded at the base Permian were locally restored and added to the cross-section. This step involves high uncertainties, especially over the palaeohighs and in areas where well control is poor, such as in the Norwegian sector. For example, it was decided not to include any Unit 6 strata (Millstone Grit Formation) in the Norwegian sector as no data support its deposition and since Unit 5 is overall concordant with the BPU. Bouroullec *et al.* (2025*b*) suggest widespread erosion during the Late Carboniferous or Permian in the northern and eastern part of the study area, supported by the occurrence in Denmark of reworked Westphalian sporomorphs in the overlying Mesozoic deposits (Nielsen and Koppelhus 1991) and the presence of Westphalian in the Midland Valley and Oslo Graben.

The tectonostratigraphic section resulting from the previous steps was then populated with stratigraphic information, such as facies belts, using the same colours as displayed in Figure 7 and in the palaeogeographical maps depicted in Bouroullec *et al.* (2025*b*, fig. 15).

Figure 14 thus highlights the proximal to distal facies changes across the study area, which can be divided into three zones located to the north of the CNSH, south of the MNSH and the area in between. The northern proximal part of the study area, located north of the newly defined CNSH (see Bouroullec *et al.* 2025*b*) is predominantly composed of alluvial systems deposited during the Tournaisian–Pendleian. River systems were transporting sediments further south, filling up topographic lows and tectonically active sub-basins with fine- to medium-grained sands with rare coarser lags, deposited in fluvial channels and crevasse splays. After the Asbian shift towards more humid climatic conditions, extensive coal seams were deposited in floodplain settings in the northern (Firth Coal Formation) and central part (Scremerston Formation) of the study area. The late Holkerian–Amsbergian strata show most syntectonic growth across active faults in this northern area.

Between the CNSH and the MNSH (see Bouroullec *et al.* 2025*b*, fig. 3), the Lower Carboniferous is thicker than in the northern part of the study area, and growth-stratigraphy is observed locally along syndepositional faults, such as the Coffee Soil Fault System (see Bouroullec *et al.* 2025*b*, fig. 16), especially pre-Brigantian. This increased accommodation in this area further enhanced the retrogradational trend observed during the Visean and early Namurian. The ‘Yoredale’ type facies was predominant during the Holkerian–Amsbergian, displaying clear cycles of marine incursions and retreats, highlighted by extensive marine limestones. Typical sequences are 5–90 m thick, and are composed of carbonate and siliciclastic deposits, including marine shales, sandstones and occasional thin coals. Locally, laterally stacking, fluvial channels and occasionally thicker (up to 25 m) incised-valley fills (see Bouroullec *et al.* 2025*b*, fig. 6) are also observed.

In the distal part of the study area, the Lower Carboniferous depositional system was predominantly marginal marine to marine, with a rather narrow marginally marine facies belt either characterized by a carbonate ramp (units 2 and 5) and/or a fluvio-deltaic coastal setting (units 3, 4 and 6). Note that the overall stacking pattern south of the MNSH was not purely aggradational but rather retrogradational, except for Unit 6 (Millstone Grit Formation) that represents a major progradational trend in the succession. This is a different model to the one proposed by Kearsey *et al.* (2019), which showed a purely aggradational trend in the southern part of the UK sector. The results presented in this paper constitute a thought-provoking attempt to synchronize the stratigraphy of the Upper Devonian and Lower Carboniferous over a large part of the North Sea. The implications regarding individual palaeobasin fills and stratal preservation on local palaeohighs were broadly out of scope. However, linking the regional tectonostratigraphic results with the new structural map presented by Bouroullec *et al.* (2025*b*, figs 17 and 18) may provide new insights locally. Future lines of research could, for example, link rapidly subsiding pull-apart basins with overthickened high TOC content lacustrine deposits with NNW–SSE-orientated offshore basins.

Conclusions

This paper has achieved a synthesis of the cross-border geology of the Upper Devonian and Lower Carboniferous of the UK, Dutch, Danish, German and Norwegian sectors of the Central and Southern North Sea through synchronizing depositional trends. Seven chronostratigraphic units were defined to better visualize lateral and temporal variations. Through summarizing stratigraphic architectures from 19 areas, a stratigraphic synthesis was established for the five national offshore sectors of the study area.

The results show that two major regional unconformities affected deposition widely in the area: the Base Visean and the Mid-Namurian unconformities. Particularly important phenomena are the development of extensive sandstones of the Fell Sandstone Formation by Arundian–Holkerian times and the development of cyclic delta-plain deposits, comprising both marine limestones and siltstones as well as coals, by Asbian and Brigantian times. The Asbian marks an isolated phase in the development of lacustrine oil shales, in specific tectonic configurations. Palynology-based vegetation reconstructions indicate a major transition near the base of the Asbian, terminating relatively arid Tournaisian and older conditions.

The most relevant stratigraphic units with regard to source-rock potential are the gas-prone coals of the Firth Coal, Scremerston and Yoredale formations. In addition, the conspicuous lacustrine–lagoonal oil shales deposited during the Asbian are very prolific. Yet, these are typically thin and difficult to establish on wireline-log data. An exception is the more temporally extensive lacustrine oil shale succession onshore Scotland in the Midland Valley Basin of Scotland (West Lothian Oil-Shale Formation). Evidence for good marine potential source rocks was not identified. The basal Namurian (Pendleian) ‘hot shale’ was described earlier in this paper as a potential oil-prone interval in a deep basinal setting (Upper Bowland Shale Formation), by analogy to what is observed in the onshore Craven Basin (UK) and the Geverik Member (The Netherlands) to the south of the study area. However, due to the high degree of thermal maturity, its character and distribution remain difficult to constrain. Finally, a conceptual cross-section was constructed, using the results and conclusions from the companion paper by Bouroullec *et al.* (2025*b*). This cross-section highlights the facies changes across the study area into three zones located to the north of the

CNSH (see Bouroullec *et al.* 2025*b*), south of the MNSH (see Bouroullec *et al.* 2025*b*) and in the intervening area.

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Author contributions **AJPH**: conceptualization (equal), data curation (equal), formal analysis (equal), funding acquisition (supporting), investigation (equal), methodology (equal), writing – original draft (lead), writing – review & editing (lead); **RB**: conceptualization (equal), data curation (supporting), formal analysis (equal), funding acquisition (supporting), investigation (equal), methodology (equal), writing – original draft (supporting), writing – review & editing (supporting); **SN**: conceptualization (equal), data curation (equal), formal analysis (equal), investigation (equal), methodology (equal), visualization (lead), writing – original draft (supporting), writing – review & editing (supporting); **DV**: conceptualization (equal), data curation (equal), formal analysis (equal), methodology (equal), visualization (equal), writing – original draft (supporting), writing – review & editing (supporting); **TIK**: conceptualization (supporting), formal analysis (supporting), investigation (supporting), writing – review & editing (supporting); **CHV**: formal analysis (supporting), methodology (supporting), validation (supporting); **NMMJ**: formal analysis (supporting), investigation (supporting), validation (supporting); **SHJP**: formal analysis (supporting), visualization (supporting); **MAS**: conceptualization (supporting), funding acquisition (supporting), project administration (supporting); **AAM**: conceptualization (equal), data curation (equal), funding acquisition (supporting), methodology (supporting), project administration (supporting), validation (supporting); **RMCHV**: conceptualization (equal), formal analysis (supporting), methodology (supporting), project administration (lead).

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Data availability The datasets generated during and/or analysed during the current study are available on the TNO-NLOG website (https://www.nlog.nl/en/knowledgebase?f%5B0%5D=publication_type%3A8).

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