The Quaternary geology of the North Sea basin

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Introduction – the Quaternary of the North Sea basin and its importance

The North Sea is a shallow (~50 to 400 m deep), ~500 km wide marine embayment that separates the UK from Scandinavia and northern Europe (Figure 1). This epicontinental shelf area has had a long and complex geological history with its present-day structural configuration largely being the result of rifting during the Jurassic–Early Cretaceous, followed by thermal subsidence (Glennie and Underhill, 1998; Zanella and Coward, 2003). Since the middle Cenozoic, the Central Graben region of the North Sea Basin has accumulated up to 3000 m of Oligocene to Holocene sediments, which locally includes more than 800 m of Quaternary sediments (Caston, 1977, 1979; Gatliff *et al*., 1994). Although a detailed understanding of the depositional history recorded by this sedimentary succession is yet to be fully established, these sediments preserve evidence for the advance and retreat of several ice sheets into the North Sea from the adjacent landmasses at different times during the Quaternary. These ice masses not only resulted in periodic erosion, but also made a significant depositional contribution to the infill of the basin.

The traditional view of the Quaternary (Pleistocene) glacial history of the North Sea suggests that during the past 500 ka the region has encountered three major glacial episodes (separated by warmer interglacial periods; Figure 2), namely the Elsterian (oldest, Marine Isotope Stage [MIS] 12), Saalian (MIS 10–6), and Weichselian (youngest, MIS 5d–2) stage glaciations (Eisma *et al*., 1979; Jansen *et al*., 1979; Caston 1979; Balson and Cameron, 1985; Sejrup *et al*., 1987, 1995, 2000, 2003; Cameron *et al*., 1987, 1992; Ehlers, 1990; Andersen *et al*., 1995; Graham *et al*., 2007, 2010, 2011; Kristensen *et al*., 2007; Bradwell *et al*., 2008; Stoker *et al*., 2011; Stewart *et al*., 2013; Ottesen *et al*., 2014). The main evidence for this tripartite subdivision is the preservation of discrete sets of palaeo-channels within the sedimentary record, which are interpreted as tunnel valleys. These landforms delimit the extent of subglacial to submarginal drainage systems developed beneath the major ice sheets that occupied the North Sea during each phase of glaciation (Wingfield, 1990; Huuse *et al*., 2001; Praeg, 2003; Lonergan *et al*., 2006; Kristensen *et al*., 2007; Stewart and Lonergan, 2011; Hepp *et al*., 2012; Janszen *et al*., 2012; Stewart *et al*., 2013).

In recent years, as more data has become available, this simple three-stage model has been questioned and there is now growing body of evidence that indicates there may have been several advances/readvances during each of the major glacial episodes (e.g. Beets *et al*., 2005; Lonergan *et al*., 2006; Stewart and Lonergan, 2011). Recent studies, utilising high-resolution marine survey data (e.g. multibeam echosounder), have presented geomorphological evidence indicating that these ice sheets extended across the continental shelves of northwest Europe to the margin of the continental shelf (e.g. Graham *et al*., 2007, 2010, 2011; Bradwell *et al*., 2008; Dunlop *et al*., 2010; Howe *et al*., 2012). Consequently it is becoming increasingly apparent that the sedimentary record within the North Sea Basin contains the key evidence to constrain the existence of Pleistocene ice sheets, and to understand the depositional and environmental changes that occurred during the intervening interglacials. During the glacial periods, the North Sea Basin provided an important pathway for large-scale transport of glacial derived sediment into the deeper Atlantic Ocean, as shown by the presence of large glacial debris fans along the northwest European continental margin (e.g. King *et al*., 1996, 1998; Bradwell *et al*., 2008; Hjelstuen *et al*., 2012). These fans were fed by ice streams comparable with those draining the modern-day Greenland and Antarctica ice caps. These corridors of relatively faster flowing ice probably formed key features of the ice sheets that occupied the North Sea Basin during the Quaternary. As a result, the Quaternary geology of the North Sea also holds key evidence for understanding the discharge and stability, and extent, of the major northern European palaeo-ice masses, in particular the British and Irish (BIIS), and Fennoscandian (FIS) ice sheets.

A brief history of research

Our understanding of the Quaternary geology of the North Sea can be linked to the advances in the technology used in the exploration for hydrocarbons and/or the siting of offshore infrastructure (e.g. oil and gas platforms, windfarms), which have occurred over recent decades. The increasing sophistication and resolution of, for example, multibeam echosounder bathymetry data as well as developments in the acquisition of 2D and 3D seismic reflection data have provided the high-quality data required to identify and analyse the geomorphological and sedimentary records left by the various Pleistocene glaciations and intervening interglacial periods within the North Sea Basin. Furthermore, deposits recovered from cores can be dated with increasing confidence using radiocarbon and Optically Stimulated Luminescence (OSL) techniques.

Regional mapping of the North Sea, during the 1970s, 1980s and into the early 1990s (e.g. Stoker *et al*., 1983, 1985; Long *et al*., 1986; Sejrup *et al*., 1987; Cameron *et al*., 1992; Gatliff *et al*., 1994), typically utilised a network of 2D seismic reflection profiles calibrated with rotary-drilled sedimentary boreholes and shallow (<6 m) cores. These integrated data permitted the development of a sedimentary and formal seismic stratigraphical framework for the Quaternary. Although there were problems with the early studies (e.g. poor core recovery, variable quality 2D seismic data, navigational accuracy) this framework remains the foundation for offshore studies of the Quaternary depositional history today. These studies demonstrated that deltaic and pro-deltaic sediments deposited by large river systems that emanated from Europe (Zagwijn, 1989; Zagwijn and Doppert 1978; Cameron *et al*., 1987; 1992; Stoker and Bent, 1987; Ekman and Scourse, 1993) dominate the Lower to Middle Pleistocene non-glacial parts of the succession. The well-defined lithostratigraphic formations within this delta system have been used to demonstrate that it prograded northwards towards the Central North Sea where it passes laterally into the penecontemporaneous marine sediments of the Aberdeen Ground Formation (Gatliff *et al*., 1994). The presence of a glacial diamicton (the "Fedje till") within the sedimentary record of the Norwegian Channel provides the earliest evidence of glacial activity within the North Sea Basin (Sejrup *et al*., 1995, 2000).

Stoker *et al*. (2011), building upon the early stratigraphic framework proposed for the UK continental shelf, divided the Quaternary succession of the Central and Northern North Sea into two major groups:

- Zulu Group, comprising a thick sequence of Early to Middle Pleistocene pro-deltaic to shallow marine sediments;
- Reaper Glacigenic Group, which includes all of the Middle to Late Pleistocene glacigenic formations within the Central and Northern North Sea.

and the Southern North Sea into three principle groups:

- Southern North Sea Deltaic Group (oldest), ranging in age from Early to Lower Middle Pleistocene;
- Dunwich Group, comprising a deltaic sequence of Lower Middle Pleistocene age;
- Californian Glacigenic Group (youngest), ranging from Middle Pleistocene to Holocene in age.

The individual formations within these groups reflect the changing depositional environments within the North Sea Basin. They can be directly correlated with comparable stratigraphical units identified in the Norwegian (see Table 11 of Stoker *et al*., 2011) and Dutch (see Table 10 of Stoker *et al*., 2011) sectors of the North Sea, providing the potential for correlating major events across the entire basin-fill. However, correlating the offshore seismic stratigraphy with the onshore subdivisions of the Quaternary, which are based upon lithostratigraphic and biostratigraphic evidence, is less straight forward and there remains a number of significant issues.

Acquisition of 3D seismic reflection data for large parts of the North Sea as part of the hydrocarbon exploration programme has continued for over 30 years. However, it is relatively recently that a selection of these datasets have been publically available to investigate the Pleistocene glacial record (Praeg, 2003; Rise *et al*., 2004; Fitch *et al.,* 2005; Lonergan *et al*., 2006; Kristensen *et al*., 2007; Kuhlmann and Wong, 2008; Lutz *et al*., 2009; Stewart, 2009). A number of the studies that utilise this high-resolution commercial 3D data, coupled with merged 2D datasets (e.g. Petroleum Geo-Services mega-survey) have begun to address issues regarding the identification, characterisation and interpretation of Middle Pleistocene subglacial tunnel valleys (Praeg, 2003; Rise *et al*., 2004; Lonergan *et al*., 2006; Lutz *et al*., 2009; Stewart, 2009), and understanding the Norwegian Channel drainage pattern (Kristensen *et al*., 2007). Mapping the distribution and relationships displayed between the tunnel valleys has led to a significant improvement in our understanding of the Quaternary glacial framework of the North Sea Basin, enabling the extent of the individual ice sheets to be established (Graham, 2007; Stewart, 2009; Graham *et al*., 2007; Stewart and Lonergan, 2011; Stewart *et al*., 2013). For example, detailed morphostratigraphic analysis of the buried tunnel valleys in the central North Sea by Stewart *et al*. (2013) has demonstrated that they form complex networks of multiple cross-cutting generations. The individual channels (300 to 3000 m wide) can be traced laterally for tens of kilometres and possess undulating basal profiles due to the pressurised nature of the meltwater flowing through the subglacial hydrological system. Stewart *et al*. (2013) concluded that tunnel valleys develop perpendicular to the margin of the retreating ice sheet and that the differences in orientation between generations reflect changes in the dynamics of the BIIS and FIS between the glaciations.

High-resolution 2D seismic datasets and single-beam (echosounder) seafloor bathymetric compilations (e.g. the Olex bathymetric database obtained by commercial fisheries) have also been utilised to improve our understanding of the more recent Weichselian glacial activity (Bradwell *et al*., 2008; Sejrup *et al*., 2009). This has enabled the detailed analysis of the spatial distribution of glacial landforms preserved on the seabed. Bradwell *et al*. (2008) used tunnel valley patterns in the Northern North Sea, the presence of large moraines to the west of Shetland, revealed by the Olex bathymetric database, and stratigraphic evidence, to demonstrate that at its maximum extent a grounded Weichselian stage ice sheet flowed north-westward across the Northern North Sea Basin, terminating at the continental-shelf edge. These authors suggested that this ice mass comprised both the BIIS and FIS, which were joined along a "confluence zone" located across the northern Orkney Islands. Furthermore, Bradwell *et al*. (2008) argued that fast-flowing ice occupied the Fair Isle Channel and was responsible for delivering glacially derived detritus to the Rona and Foula sediment wedges located at the continental-shelf edge. A number of other models for the Weichselian Stage glaciation of the North Sea (Graham *et al*., 2007, 2011; Sejrup *et al*., 2009) also require the BIIS and FIS to have converged forming a confluence zone within the central part of the basin located to the north of, and between Dogger Bank and Denmark. However, the actual limits of these major ice masses within the southern North Sea remain poorly understood and constrained (Figure 3) (Catt, 1991; Sejrup *et al*., 2009).

A number of sedimentological studies have also begun to take advantage of high-precision AMS radiocarbon dating of carbonate material to provide a greater chronological control on the Late Quaternary sequence within the North Sea (Sejrup *et al*., 2009; Graham *et al*., 2010). Graham *et al*. (2010) combined a detailed interpretation of a sequence of diamictons and soft muds recovered from a borehole (30 m deep) with 2D/3D seismic data from the Witch Ground in the Central North Sea to investigate the late Weichselian glacial-to-post-glacial history of this area. They concluded that this sequence records an initial period of ice-sheet advance and overriding, followed by deglaciation and subsequent post-glacial glaciomarine-to-marine sedimentation. The presence of a buried suite of streamlined subglacial bedforms led Graham *et al*. (2010) to conclude that Witch Ground was overridden by fast flowing (SE-NW) ice. AMS ^{14}C dating obtained by these authors was used to confirm that ice-stream activity and extensive glaciation of this part of the North Sea occurred during the Last Glacial Maximum, between c. 30 and 16.2 ^{14}C ka BP.

A small number of studies have also used micromorphology, as well as macroscale analysis of cores, as an additional tool in providing a detailed genetic interpretation of the glacigenic sediments (Carr *et al*., 2006). Carr *et al*. (2006) presented the results of seismic, sedimentological and micromorphological studies to reconstruct the depositional processes of regionally extensive seismic units across the North Sea Basin. Thin section micromorphology was used to discriminate between subglacial and glacimarine sediments, and thereby derive a process-based interpretation of the sequences revealed in the cores. The application of this microscale analysis allowed Carr *et al*. (2006) to reinterpret the depositional setting of key formations within the North Sea Basin, with consequent stratigraphic implications. By comparing their North Sea data with thin sections from comparable deposits in Svalbard and Alaska these authors argue that subglacial conditions result in the formation of a diagnostic suite of microscale deformation structures that can be used to discriminate between subglacial tills and diamictons deposited in ice-proximal and distal glacimarine environments. The resulting detailed sedimentological data has the potential to provide a more robust the interpretation of the depositional setting of the Quaternary offshore sequences required to reconstruct the extent, timing and dynamics of the Weichselian and other glaciations to have affected the North Sea Basin.

From the Last Glacial Maximum (LGM; ~29-22 kaBP) to the present day, the North Sea Basin has undergone widespread ice retreat and concomitant sea-level rise and terrestrial inundation. The interaction of terrestrial and marine processes during inundation of low-lying coastal areas has shaped the modern bathymetry and coastlines of the North Sea. Marine transgression also impacted the prehistoric human settlements and migration patterns. During the LGM, the global sea-level was approximately 118-135 m lower than today (e.g. Fairbanks, 1989; Bard *et al.*, 1990; Hanebuth *et al.*, 2000; Yokoyama *et al.*, 2000). Post–glacial barystatic (previously referred to as "eustatic", see IPCC, 2013 for definition) sea–level rise was strongly asymmetric in nature. An initial, relatively slow Late Pleistocene barystatic sea–level rise was followed by an interval of rapid deglacial rise between 17 kaBP and 7 kaBP (e.g. Fairbanks, 1989; Fleming *et al.*, 1998; Bassett *et al*., 2005), rates then decreased significantly (e.g. Jelgersma, 1979; Fairbanks, 1989; Bard *et al.*, 1990; Behre, 2007; Vink *et al*., 2007; Smith *et al*., 2011; Austermann *et al*., 2013). During the phase of rapid deglacial rise, melt-water pulse events punctuated the steady rate of rise with periods of more rapid rise, such as the MWP-1A event occurring at around 14.5 kaBP, contributing approximately 14 m globally (Deschamps *et al.*, 2012). These MWP events coincide with periods of ice sheet retreat in the BIIS and FIS (e.g. Sejrup *et al*., 2000; Sejrup *et al.*, 2009). Relative sea-level rise was different all around the North Sea due to a combination of barystatic sea-level rise, local sediment supply and compaction, and glacio-isostatic adjustment. Late Pleistocene to present-day relative sea-level curves from sites in the North Sea have undergone many iterations (e.g. Jelgersma, 1979; Behre, 2007; Vink *et al*., 2007; Bungenstock and Weerts, 2010; Shennan *et al*., 2012). These relative sea-level (RSL) curves are site-specific, but glacio-isostatic adjustment (GIA) modelling can provide RSL curves for a given location. Refined local ice histories are required to accurately model glacial-isostatic adjustment. However, significant disagreement remains as to the maximum extent of the BIIS and FIS (Figure 3). Earlier authors, such as Sejrup *et al.* (1987), Long *et al.* (1988) and Ehlers and Wingfield (1991) interpreted Scottish onshore moraines to be terminal, constraining a much smaller ice sheet which did not coalesce with the FIS. Jansen *et al.* (1979) interpreted coalescence in the Northern North Sea from glacial sediments. More recent authors, such as Carr *et al.* (2006), Ballantyne (2010; based on Sejrup *et al.,* 2005 and Bradwell *et al.,* 2008) and Sejrup *et al.* (2016) present evidence for much larger ice sheets, extending to the shelf edge of the Atlantic margin and coalescing during the LGM. Despite these recent knowledge advancements, the timing and nature (location and thickness) of the BIIS-FIS coalescence is poorly constrained. Furthermore, Clark *et al.* (2012) also point out that maximum extents in Figure 3 are diachronous, and the collapse of the BIIS and FIS remains the focus of ongoing research (e.g. Sejrup *et al.*, 2016). The unknowns around the history of ice in the North Sea limit GIA models. The most recent ice sheet reconstructions used as inputs in GIA modelling of the BIIS (e.g. Kuchar *et al.*, 2012) are from Brooks *et al.* (2008) and Hubbard *et al.* (2009). Brooks *et al.* (2008) ice sheets are based purely on geomorphological constraints, whereas Hubbard *et al.* (2009) use reinterpretations of trimline data (e.g. Fabel *et al.*, 2012) to inform a thermomechanical model. However, neither model accounts for BIIS-FIS coalescence. Furthermore, there is a lack of constrained sea-level index points in the region which are required to test model outputs.

Palaeogeographic maps of the North Sea area are starting to provide more detail and higher temporal resolution (e.g. Coles, 1998; Shennan *et al*., 2000; Clark *et al*. 2012; Sturt *et al*., 2013). These will continue to be refined as more chronostratigraphic data becomes available. The transition from glacimarine to (shallow) temperate–marine conditions took place through the Late–Glacial and Early Holocene (Graham *et al*., 2011; Clark *et al*., 2012). Between ~9 and ~7 kaBP, the North Sea became connected to the English Channel. Full-marine conditions in the North Sea basin were only established by ~6 kaBP (Graham *et al*., 2011). The redistribution of Pleistocene deposits since the onset of the marine transgression over the antecedent land surface is a key process in the distribution of the present-day sea-bed sediment (Cameron *et al*., 1992). Coastal erosion is an important source of siliciclastic sediment supply to the North Sea. The interaction of landscape change and Mesolithic human migration patterns has been a focus for many years. Reid (1913) was the first to suggest a landbridge between Britain and the continent, the so-called 'Doggerland', composed predominantly of fens and wetlands. One of the most well-studied Holocene landscapes and most prolific archaeological sites is the Dogger Bank, which forms a topographic high in the Southern North Sea. The shallowest point on the southwestern Dogger Bank is only 11–12m below today's sea-surface (Cameron *et al*., 1992; von Haugwitz and Wong, 1988). Fitch *et al*. (2005) present a simplified stratigraphic framework for the Late Pleistocene and Holocene of the Dogger Bank. Due to glacitectonic and glacio-isostatic effects, transgressive sedimentation and erosion it is unlikely that the present-day bathymetry is an accurate representation of the Early Holocene (Coles, 1998; Fitch *et al*., 2005).

Although, as outlined above, there have been significant advances in the acquisition and interpretation of offshore data, a number of issues still remain regarding the evolution of the North

Sea Basin during Quaternary. The papers in this special issue address some of these outstanding issues.

Contents of the Special Issue

This special issue of the Journal of Quaternary Science contains a selection of papers stemming from the Quaternary Research Association's Annual Discussion Meeting held in Edinburgh in 2015. The aim of this international meeting was to bring together scientists working in the North Sea and surrounding areas and provide a forum in which to exchange views and information, and discuss new ideas regarding the Quaternary evolution of the North Sea basin on a variety of time scales, its glacial and interglacial successions, its archaeological record of human occupation, and the recent advances in the mapping of marine habitats and their conservation. This collection of 12 papers represents the range of science presented at this meeting from the depositional history of the earliest part of the Quaternary sequence of the central North Sea (Lamb *et al*., 2016) through to understanding submerged Holocene landscapes and the early human occupation of the North Sea Basin (Ballin, 2016; Bicket *et al*., 2016) (see Figures 1 and 2).

The papers by Lamb *et al*. (2016), Buckley (2016) and Westaway (2016) tackle a number of issues regarding the Early to Middle Quaternary history of the North Sea (Figure 2). **Lamb *et al.*** (2016) investigate the origins of a large number of elongate trough-like features observed within the central North Sea Basin (6 on Figure 1). These authors use 3D reflection seismic and well log data to map out the spatial extent of these subaqueous bedforms, which they conclude formed on the slope of a rapidly prograding, large clinoform set. Lamb *et al*. argue that the majority of these troughs were excavated perpendicular to the strike of the slope by density-driven downslope flows. However, a number of troughs that formed parallel to the strike of the slope cannot be readily explained by downslope processes alone.

Buckley employs 3D reflection seismic over a 700 km^2 area (UK Quad 16), and a suite of geophysical data from a borehole to investigate the evidence for an Early Pleistocene ice sheet in the central North Sea (3 in Figure 1). The base and top of the studied interval are bounded by erosion surfaces. The age of the interval of interest is constrained by the identification of the Jaramillo Normal sub-chron. Observational evidence used to support an Early Pleistocene age, in addition to features identified from nearby blocks (UK Quads 22 and 21, and Norwegian Quad 15), include Mega-scale Glacial Lineations (MSGLs), highly immature sand, tectonised clay units that contain angular clasts. Buckley ends by calling for a reappraisal of the Early Pleistocene stratigraphy, including the glacial history and depositional environments preserved from this time period.

A refined isostatic compensation model of linked vertical crustal movements during the Quaternary are presented by **Westaway** (2016). New onshore (cave levels and fluvial terrace staircases) and offshore (reflection seismic) datasets are employed to build on the idea of coupled crustal motion processes: North Sea subsidence and British uplift (11 on Figure 1). Westaway argues for a process of lower-crustal flow driven by a lateral pressure gradient set-up the surface processes. The invoked erosional isostatic compensation is additional to the better known mantle-driven isostacy, but is also distinct in that it is irreversible.

Glacier induced deformation can have a profound impact on both the structural and sedimentological architecture of glacigenic sequences. **Pedersen and Boldreel** (2016) describe how the Quaternary and Lower and Upper Cretaceous bedrock geology in the Danish sector of the North Sea (9 on Figure 1) have been affected by the development of a large-scale glaciotectonic complex – the Jammerbugt Glaciotectonic Complex. The folding and thrusting which characterise this recently discovered complex occurs above a prominent basal detachment situated at a depth of up to 400 m below sea level. The authors conclude that this glaciotectonic deformation is Saalian in age and suggest that the source of the detached thrust blocks was in the Skagerrak Sea, and contributed to formation of the Skagerrak depression; an early stage of the Norwegian Trench.

The glacitectonic theme is continued in the paper by **Vaughan-Hirsch and Phillips** (2016). This paper presents the results of a high-resolution 2D seismic survey of mid-Pleistocene glaciogenic sediments in the Central Graben region of the central North Sea (10 on Figure 1). The authors describe a c. 5-6 km wide imbricate thrust stack formed at the margin of a southerly advancing mid-Pleistocene ice sheet. Vaughan-Hirsch and Phillips (2016) argue that the major décollement surface marking the base of the evolving thrust-stack developed within a laterally extensive sand sheet in the upper Aberdeen Ground Formation. Detachment within the sediment pile is thought to have occurred in response to the over-pressurisation of groundwater due to rapid ice advance, linking the development of large-scale thrust complexes to surge-type behaviour.

A microscale approach to the analysis of glacially deformed sediments and bedrock is provided by the paper by **Gehrmann et al**. (2016). These authors examine the complex microscale deformation fabrics developed with a prominent thrust fault deforming the south-western limb of the Wissower Bach Syncline on the Jasmund Peninsula on the Baltic coast of northeast Germany (5 on Figure 1). This syncline forms part of a large-scale glacitectonic complex that deforms the Cretaceous chalk and Pleistocene sediments. Gehrmann *et al*. (2016) have combined a detailed 3D microstructural model of the deformed glacial sediments with macroscale observations to develop of a detailed model for the evolution of the Wissower Bach Syncline during glacitectonism, including the localised reactivation of the thrust during ice sheet retreat.

The relationships between the ice occupying the North Sea Basin and the onshore Quaternary record in the UK have been investigated in the papers by Lee *et al*. (2016), White *et al*. (2016), Merritt *et al*. (2016) and Evans *et al*. (2016) (7, 12, 4 and 8 on Figure 1). **Lee *et al*.** (2016) identify six tectonostratigraphic-parasequence assemblages (A1-A6) to help resolve controversies regarding the archive of Middle Pleistocene glacial history preserved in northern East Anglia (7 in Figure 1). The approach of mapping tectonstratigraphic parasequences, founded in detailed field observations, have revealed multiple advances by Pennine or North Sea lobes of the British Ice Sheet into the south-western margins of the southern North Sea basin. Also, an angular unconformity between A2 and A3 indicates a significant period of landscape evolution. The authors discuss substrate rheology (lithology, pore water availability, permeability and porosity) as a control on the character of the basal contact to the tectonostratigraphic parasequences, which can be a sharp sedimentary surface, or form a glacitectonic zone. This approach advocated by Lee et al. will help efforts to link onshore and offshore Quaternary stratigraphy in the future.

The enigmatic onshore record of the extent and timing of Middle Pleistocene glaciations is also a focus of **White *et al*.** (2016). The authors argue for extensive ice cover during MIS 8 on the western edge of the south North Sea basin (12 on Figure 1) using the depositional (e.g. the Wragby Till) and geomorphological records, uplift/incision modelling, and the absence of MIS 11-9 deposits. They also state that there is no compelling evidence for MIS 6 aged lowland glaciations in their study area. White et al. end with a call to better distinguish between Anglian and post-Anglian glacial deposits in areas beyond the Devensian ice limits to further refine palaeogeographic limits of Middle Pleistocene ice limits.

Merritt *et al*. (2016) present a comprehensive review of over 175 years of research into the Middle to Late Weichselian (Devensian) glaciation of northeast Scotland. This onshore region, and surrounding seabed, provide detailed geomorphological and sedimentary records which can be used to decipher the interactions between and dynamics the former BIIS and FIS within the North Sea Basin. Merritt *et al*. (2016) erect a 12-stage event stratigraphy which records the evolution of the north-eastern quadrant of the BIIS which reached its maximum spatial extent during the late Middle to early Late Weichselian.

The paper by **Evans *et al*.** provides a detailed description of stratigraphy and chronology of a proglacial ice-dammed lake in the Vale of Pickering located adjacent to the North Sea coast in North

Yorkshire, UK (4 on Figure 1). They present four new optically stimulated luminescence dates from the sedimentary record preserved within Glacial Lake Pickering to demonstrate that the lake was dammed by the North Sea Lobe of the BIIS during the Dimlington Stadial (24–11 ka cal BP). A further date is used to constrain the age of reworking of the overlying coversand during the early part of the Holocene, immediately after the Younger Dryas.

Current research into the Holocene and human occupational history of the North Sea are represented by papers by Bickett *et al*. (2016) and Ballin (2016) (Figure 2). **Bickett et al.** (2016) present new high-resolution geophysical data from shallow-water nearshore areas offshore Northumberland; part of the so-called 'white ribbon' (2 on Figure 1). The authors use this data to investigate the relationship between Mesolithic settlements and Holocene palaeogeographic configuration that was evolving during marine transgression. The integration of bathymetry, LiDAR, reflection seismic, bedrock geology and archaeological datasets underpin reconstructions of the palaeogeography in the study area, including identification of bedrock palaeochannels and relict coastlines. The approach taken here could be applied to other offshore sites to improve the management of coastal prehistoric archaeological heritage.

The paper by **Ballin** discusses how post-glacial sea-level rise may have led to material cultural diversification and 'atomization' of geographically extensive cultures or social territories in the Scandinavian sectors of the North Sea and Baltic Sea (1 on Figure 1). The author presents evidence to show that the resulting smaller social territories, with their associated material cultures, began to merge, possibly due to the development of better means of transport with the developing North Sea increasingly providing the means of communication.

Final remarks

We are in the middle of a data revolution for the Quaternary North Sea. This compilation of papers adds to our rapidly expanding understanding of this area. The advance, interaction, coalescence and retreat of ice sheets during the Quaternary in the North Sea area has resulted in a complicated stratigraphic record of palaeoenvironmental changes, and much work remains to be done to link the onshore and offshore records. There is the opportunity to use the glacial and interglacial Quaternary archive of the North Sea basin-fill, and for this area to become the world's best-constrained offshore field laboratory in the study of the timing of, and response to, the advance and retreat of ice sheets. The widespread marine transgression since the Last Glacial Maximum resulted in redistribution of sediment, realignment of coastlines, and influenced ancient human settlement and migration patterns. Thus, the stratigraphic evolution of the Quaternary North Sea Basin is a crucial record to help understand climate and shoreline responses, and so predict and mitigate future environmental change.

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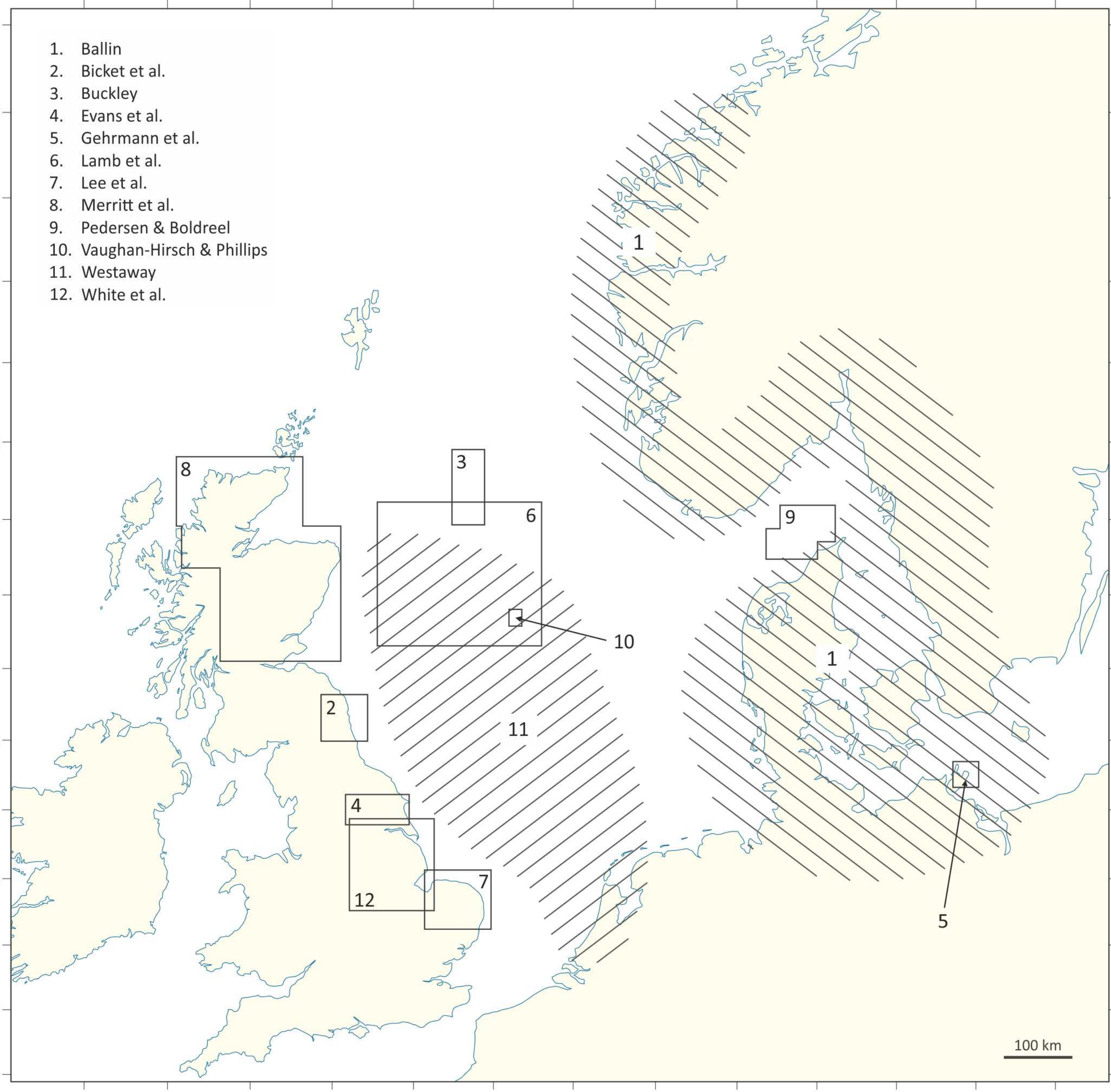
Figures

Figure 1. Location map illustrating the diverse geographic areas covered by the contributions in this special volume.

Figure 2. Stratigraphic column of the Quaternary with timescale, palaeomagnetic column, marine isotope stages, and regional stage divisions. The right hand column indicates the stratigraphic range of contributions to this special volume. Adapted from Cohen and Gibbard (2011).

Figure 3. Compiled map of published Last Glacial Maximum ice sheet extents, highlighting the uncertainty, disagreement and difficulty in interpreting maximum ice extents, particularly in the Southern North Sea. Black lines represent ice sheet reconstructions which coalesce over the North Sea. Grey lines represent no coalescence. Red lines represent GIA model input ice sheets. The purple line represents terminal moraine data from the BRITICE project (Clark *et al*., 2004). The blue line represents latest interpretations from Sejrup *et al*., 2016.



1. Ballin
2. Bicket et al.
3. Buckley
4. Evans et al.
5. Gehrmann et al.
6. Lamb et al.
7. Lee et al.
8. Merritt et al.
9. Pedersen & Boldreel
10. Vaughan-Hirsch & Phillips
11. Westaway
12. White et al.
64°N
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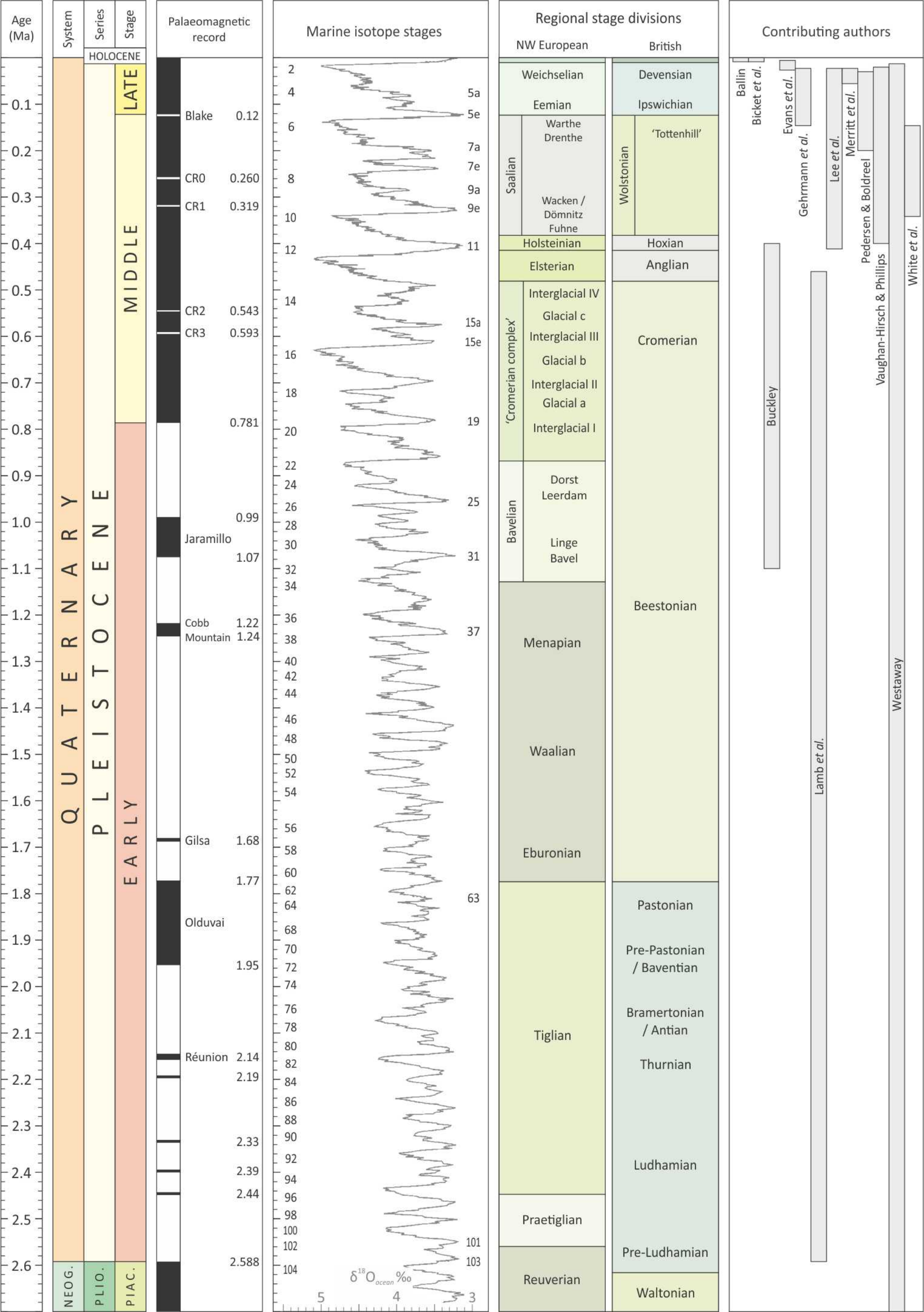

Age (Ma)
System
Series
Stage
Palaeomagnetic record
Marine isotope stages
Regional stage divisions
NW European
British
Contributing authors
HOLOCENE
QUATERNARY
PLEISTOCENE
LATE
MIDDLE
EARLY
NEOG.
PLIO.
PIAC.
Blake 0.12
CR0 0.260
CR1 0.319
CR2 0.543
CR3 0.593
0.781
0.99
Jaramillo
1.07
Cobb Mountain 1.22 1.24
Gilsa 1.68
1.77
Olduvai
1.95
Réunion 2.14
2.19
2.33
2.39
2.44
2.588
δ18Oocean ‰
Weichselian
Eemian
Saalian
Warthe
Drenthe
Wacken / Dömnitz Fuhne
Holsteinian
Elsterian
'Cromerian complex'
Interglacial IV
Glacial c
Interglacial III
Glacial b
Interglacial II
Glacial a
Interglacial I
Bavelian
Dorst
Leerdam
Linge
Bavel
Menapian
Waalian
Eburonian
Tiglian
Praetiglian
Reuverian
Devensian
Ipswichian
Wolstonian
'Tottenhill'
Hoxian
Anglian
Cromerian
Beestonian
Pastonian
Pre-Pastonian / Baventian
Bramertonian / Antian
Thurnian
Ludhamian
Pre-Ludhamian
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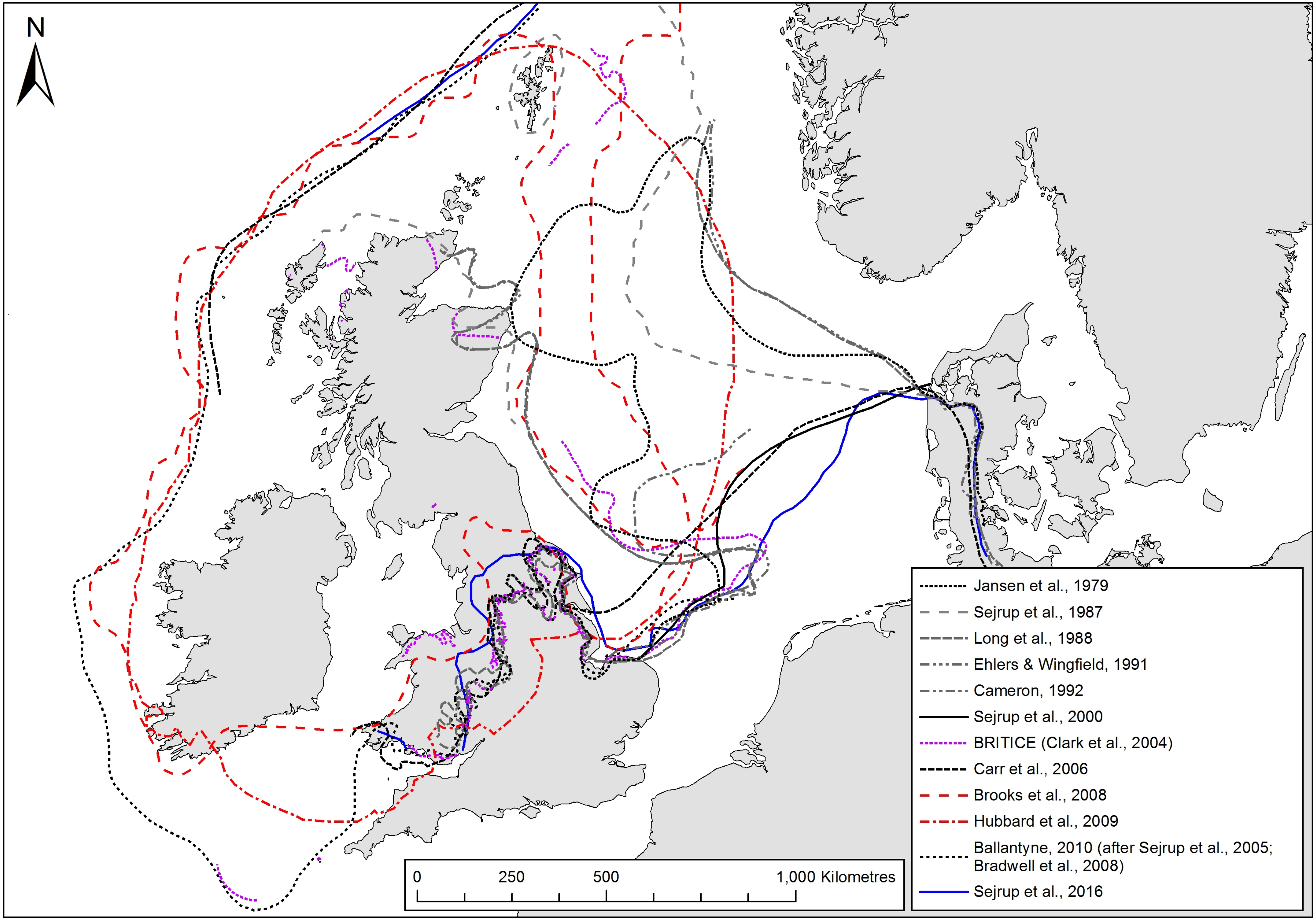
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Jansen et al., 1979
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BRITICE (Clark et al., 2004)
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Brooks et al., 2008
Hubbard et al., 2009
Ballantyne, 2010 (after Sejrup et al., 2005; Bradwell et al., 2008)
Sejrup et al., 2016
0
250
500
1,000 Kilometres